U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
PB-286 836

Chemical and Physical Effects of Municipal Landfills on Underlying Soils and Groundwater

(U.S.) Army Engineer Waterways Experiment Station, Vicksburg, MI

Prepared for

Municipal Environmental Research Lab, Cincinnati, OH

May 78

United States
Environmental Protection
Agency

Municipal Environmental Research
Laboratory
Cincinnati OH 45268

EPA-600/2-78-096
May 1978

Research and Development

PB 286836

EPA

Chemical and Physical Effects of Municipal Landfills on Underlying Soils and Groundwater

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-78-096	2.	3. RECIPIENT'S ACCESSION NO. PB286836
4. TITLE AND SUBTITLE Chemical and Physical Effects of Municipal Landfills on Underlying Soils and Groundwater		5. REPORT DATE May 1978 (Issuing Date) 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) U.S. Army Engineer Waterways Experiment Station		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Environmental Effects Laboratory U.S. Army Engineer Waterways Experiment Station Vicksburg, Mississippi 39180		10. PROGRAM ELEMENT NO. 1DC618 11. CONTRACT/GRANT NO. IAG-D4-0569
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory--Cin.,OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED Final,June 1975-December 1975 14. SPONSORING AGENCY CODE EPA/600/14
15. SUPPLEMENTARY NOTES Robert E. Landreth, Project Officer, 684-7871		

16. ABSTRACT Three municipal landfill sites in the eastern and central United States were studied to determine the effects of the disposal facilities on surrounding soils and groundwater . Borings were made up the groundwater gradient, down the groundwater gradient and through the landfill. Soil and groundwater samples from the test borings were examined. Groundwater samples were analyzed chemically. Soil samples were tested physically and distilled water extracts and nitric acid digests of the soils were analyzed chemically. Groundwater samples from under and downgradient from the landfill showed elevated levels of sulfate in every case. At some sites increased levels of nitrate, total organic carbon and cyanide could be related to the presence of the landfill. No changes in physical characteristics could be related to the presence of the landfill at any site. No evidence was found in this study to indicate that sub-landfill soils seal themselves. Distilled water extracts prepared from soil samples showed consistently low levels for all soluble constituents. Generally, there was more sulfate, chloride, organic carbon, nitrate and high levels of trace metals in extracts of soils from under the landfill than from soils collected at similar depths outside the landfill. Nitric acid digests of soil samples showed great variability in chemical composition. At two of the three sites; iron, manganese, boron, beryllium and zinc were found in higher concentrations in nitric acid digests immediately under the landfill. The results of this investigation indicate that chemical characteristics but, not physical characteristics were altered in sub-landfill soils. Removal of pollutants from leachate through the action of soil was observed for only a very limited number of pollutants.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Chemical Analysis Leaching Soil Chemistry	Solid Waste Pollutant Migration Groundwater Pollution Municipal Landfill	13B

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES 156
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE A08-A01

EPA Form 2220-1 (9-73)

U.S. GOVERNMENT PRINTING OFFICE: 1978— 757-140/1354

EPA-600/2-78-096
May 1978

CHEMICAL AND PHYSICAL EFFECTS OF MUNICIPAL LANDFILLS ON UNDERLYING SOILS AND GROUNDWATER

by

Environmental Effects Laboratory
U.S. Army Engineer Waterways Experiment Station
Vicksburg, Mississippi 39180

Interagency Agreement No. EPA-IAG-D4-0569

Project Officer

Robert E. Landreth
Solid and Hazardous Waste Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

DISCLAIMER

This report has been reviewed by the Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U. S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This report presents results from the field investigation of three municipal solid waste landfill sites to determine their effects on surrounding soils and groundwater. It provides basic data on the potential pollution from land disposal of municipal solid waste and will add to the knowledge required to determine the environmental consequences of the land as a rector of waste materials.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

Three municipal landfill sites in the eastern and central United States were studied to determine the effects of the disposal facilities on surrounding soils and groundwater. Borings were made up the groundwater gradient, down the groundwater gradient and through the landfill. Soil and groundwater samples from the test borings were examined. Groundwater samples were analyzed chemically. Soil samples were tested physically and distilled water extracts and nitric acid digests of the soils were analyzed chemically.

Groundwater samples from under and downgradient from the landfill showed elevated levels of sulfate in every case. At some sites increased levels of nitrate, total organic carbon and cyanide could be related to the presence of the landfill.

No changes in physical characteristics could be related to the presence of the landfill at any site. No evidence was found in this study to indicate that sub-landfill soils seal themselves.

Distilled water extracts prepared from soil samples showed consistently low levels for all soluble constituents. Generally, there was more sulfate, chloride, organic carbon, nitrate and higher levels of trace metals in extracts of soils from under the landfill than from soils collected at similar depths outside the landfill.

Nitric acid digests of soil samples showed great variability in chemical composition. At two of the three sites; iron, manganese, boron, beryllium and zinc were found in higher concentrations in nitric acid digests immediately under the landfill.

The results of this investigation indicate that chemical characteristics; but, not physical characteristics were altered in sub-landfill soils. Removal of pollutants from leachate through the action of soil was observe[illegible] only a very limited number of pollutants.

This report was submitted in partial fulfillment of Interagency Agreement Number EPA-IAG-D4-0569 by the U. S. Army Engineer Waterways Experiment Station under the sponsorship of the U. S. Environmental Protection Agency. This report covers the period from June 1975 to December 1977.

CONTENTS

Foreword iii
Abstract iv
Figures vi
Tables ix
Acknowledgment xiii

1. Introduction 1
2. Conclusions 7
3. Recommendations 9
4. Methods and Materials 10
    Site selection 10
    Sampling procedures 13
    Sample handling and preparation techniques 16
    Physical testing methods 21
    Chemical analytical methods 22
5. Results and Discussion 26
    Physical testing 26
    Chemical analyses of groundwater 31
    Chemical analyses of distilled water extracts 36
    Chemical analyses of nitric acid extracts 68
    Discussion 95

References 102
Appendices 104

A. Sub-surface information for Site A 104
B. Sub-surface information for Site B 117
C. Sub-surface information for Site C 128

FIGURES

Number Page

1 Sketch of typical landfill showing sampling plan 3

2 Sketch of Hvorslev sampler 14

3 Sketch of split spoon sampler 15

4 Topographic map of site A 17

5 Topographic map of site B 18

6 Topographic map of site C 19

7 Variation of total organic carbon (TOC) concentration in distilled water extracts of soil/sediment samples with elevation in boring 1 at site A 51

8 Variation of sodium concentration in distilled water extracts of soil/sediment samples with elevation in borings 2, 6, and 7 at site A 52

9 Variation of cyanide concentration in distilled water extracts of soil/sediment samples with elevation in boring 3 at site B 53

10 Variation in total organic carbon (TOC) concentration in distilled water extracts of soil/sediment samples with elevation in borings 2, 3, and 6 at site B 54

11 Variation of calcium concentration in distilled water extracts of soil/sediment samples with elevation in borings 3, 5, and 6 at site B 55

12 Variation of iron concentration in distilled water extracts of soil/sediment samples with elevation in boring 2 at site B . 56

13 Variation of sodium concentration in distilled water extracts of soil/sediment samples with elevation in borings 2, 3, and 5 at site B 57

14 Variation of boron concentration in distilled water extracts of soil/sediment samples with elevation in boring 2 at site B . 58

Number Page

15 Variation of chromium concentration in distilled water extracts of soil/sediment samples with elevation in boring 2 at site B 59

16 Variation of zinc concentration in distilled water extracts of soil/sediment samples with elevation in boring 2 at site B . 60

17 Variation of calcium concentration in distilled water extracts of soil/sediment samples with elevation in borings 1, 2, and 9 at site C 61

18 Variation of zinc concentration in distilled water extracts of soil/sediment samples with elevation in boring 1 at site C . 62

19 Horizontal variation in chemical composition of distilled water extracts at site A 65

20 Horizontal variation in chemical composition of distilled water extracts at site B 66

21 Horizontal variation in chemical composition of distilled water extracts at site C 67

22 Variation of boron concentration in nitric acid digests of soil/sediment samples with elevation in borings 1, 2, and 6 at site A 81

23 Variation of beryllium concentration in nitric acid digests of soil/sediment samples with elevation in boring 3 at site A . 82

24 Variation of selenium concentration in nitric acid digests of soil/sediment samples with elevation in borings 3 and 6 at site A 83

25 Variation of arsenic concentration in nitric acid digests of soil/sediment samples with elevation in borings 2, 3, and 5 at site B 84

26 Variation of copper concentration in nitric acid digests of soil/sediment samples with elevation in borings 2 and 5 at site B 85

27 Variation in manganese concentration in nitric acid digests of soil/sediment samples with elevation in borings 2, 3, and 5 at site B 86

28 Variation of lead concentration in nitric acid digests of soil/sediment samples with elevation in borings 2 and 3 at site B 87

Number Page

29 Variation of zinc concentration in nitric acid digests of soil/sediment samples with elevation in borings 2, 3, and 5 at site B 88

30 Variation of beryllium concentration in nitric acid digests of soil/sediment samples with elevation in boring 2 at site C . . 89

31 Variation of iron concentration in nitric acid digests of soil/sediment samples with elevation in boring 1 at site C 90

32 Variation in manganese concentration in nitric acid digests of soil/sediment samples with elevation in borings 1 and 3 at site C 91

33 Variation of nickel concentration in nitric acid digests of soil/sediment samples with elevation in borings 1, 6, and 9 at site C 92

34 Variation of zinc concentration in nitric acid digests of soil/sediment samples with elevation in borings 1, 2, 3, 6, and 9 at site C 93

35 Horizontal variation in chemical composition of nitric acid digests at site A 96

36 Horizontal variation in chemical composition of nitric acid digests at site B 97

37 Horizontal variation in chemical composition of nitric acid digests at site C 98

A-1 Water table map of site A 105

B-1 Water table map of site B 118

C-1 Water table map of site C 129

TABLES

Number Page

1 Chemical Constituents Analytically Determined in Groundwater Filtrates, Distilled Water Extracts and Nitric Acid Digests . . 5

2 Summary of the Characteristics of the Three Sites Selected for Study 11

3 Character of Waste Deposited in Landfill at Site A as Listed by the Municipality 12

4 Methods of Preservation of Water Extracts and Filtered Groundwater Subsamples for Chemical Analysis 20

5 Descriptions of USCS Soil Groups 23

6 Techniques Used in the Analysis of Distilled Water Extracts, Nitric Acid Digests and Groundwater Filtrates 24

7 Physical Testing Data for Samples from Site A 27

8 Physical Testing Data for Samples from Site B 28

9 Physical Testing Data for Samples from Site C 29

10 Comparison of the Physical Properties of the Uppermost Samples Collected Within and Outside the Landfills 30

11 Chemical Composition of Groundwater Obtained from Borings at Landfill A 32

12 Chemical Composition of Groundwater Obtained from Borings at Landfill B 33

13 Chemical Composition of Groundwater Obtained from Borings at Landfill C 34

14 Results of Analysis of Variance for Groundwater Chemistry 35

15 Analyses of Distilled Water Extracts of Soil Samples from Experimental Borings at Site A 38

Number Page

16 Analyses of Distilled Water Extracts of Soil Samples from Control Borings at Site A 40

17 Analyses of Distilled Water Extracts of Soil Samples from Experimental Borings at Site B 41

18 Analyses of Distilled Water Extracts of Soil Samples from Control Borings at Site B 42

19 Analyses of Distilled Water Extracts of Soil Samples from Experimental Borings at Site C 43

20 Analyses of Distilled Water Extracts of Soil Samples from Control Borings at Site C 44

21 Results of Randomization Test on Distilled Water Extracts of Soil Samples Directly Under the Landfills and at Comparable Depths Outside the Landfills 45

22 Correlation of Chemical Analyses of Distilled Water Extracts of Soil Samples with Sample Elevation at Site A 48

23 Correlation of Chemical Analyses of Distilled Water Extracts of Soil Samples with Sample Elevation at Site B 49

24 Correlation of Chemical Analyses of Distilled Water Extracts of Soil Samples with Sample Elevation at Site C 50

25 Analyses of Nitric Acid Digests of Soil Samples from Experimental Borings at Site A 69

26 Analyses of Nitric Acid Digests of Soil Samples from Control Borings at Site A 71

27 Analyses of Nitric Acid Digests of Soil Samples from Experimental Borings at Site B 72

28 Analyses of Nitric Acid Digests of Soil Samples from Control Borings at Site B 73

29 Analyses of Nitric Acid Digests of Soil Samples from Experimental Borings at Site C 74

30 Analyses of Nitric Acid Digests of Soil Samples from Control Borings at Site C 75

31 Results of Randomization Test on Nitric Acid Digests of Soil Samples Directly Under the Landfills and at Comparable Depths Outside the Landfills 76

Number Page

32 Correlation of Chemical Analyses of Nitric Acid Digests of Soil Samples with Sample Elevation at Site A 78

33 Correlation of Chemical Analyses of Nitric Acid Digests of Soil Samples with Sample Elevation at Site B 79

34 Correlation of Chemical Analyses of Nitric Acid Digests of Soil Samples with Sample Elevation at Site C 80

35 Comparison of Average Chemical Composition of Groundwater and Soil Samples from Experimental and Control Borings for all Sites 100

A-1 Log of Boring 1 at Site A 106

A-2 Log of Boring 2 at Site A 107

A-3 Log of Boring 3 at Site A 108

A-4 Log of Boring 4 at Site A 109

A-5 Log of Boring 5 at Site A 110

A-6 Log of Boring 6 at Site A 111

A-7 Log of Boring 7 at Site A 112

A-8 Log of Boring 8 at Site A 113

A-9 List of Samples Examined from Site A 114

B-1 Log of Boring 1 at Site B 119

B-2 Log of Boring 2 at Site B 120

B-3 Log of Boring 3 at Site B 121

B-4 Log of Boring 4 at Site B 122

B-5 Log of Boring 5 at Site B 123

B-6 Log of Boring 6 at Site B 124

B-7 Log of Boring 7 at Site B 125

B-8 Log of Boring 8 at Site B 126

B-9 List of Samples Examined from Site B 127

C-1 Log of Boring 1 at Site C 130

Number Page

C-2 Log of Boring 2 at Site C 131

C-3 Log of Boring 3 at Site C 132

C-4 Log of Boring 4 at Site C 133

C-5 Log of Boring 5 at Site C 134

C-6 Log of Boring 6 at Site C 135

C-7 Log of Boring 7 at Site C 136

C-8 Log of Boring 8 at Site C 137

C-9 Log of Boring 9 at Site C 138

C-10 List of Samples Examined from Site C 139

ACKNOWLEDGEMENTS

This field investigation was conducted by the Environmental Effects Laboratory and the Soils and Pavements Laboratory of the U. S. Army Engineer Waterways Experiment Station (WES) under sponsorship of the Municipal Environmental Research Laboratory, Environmental Protection Agency.

The coordinating author was Dr. Philip G. Malone. The authors included Dr. Bobby L. Folsom, Mr. James M. Brannon, Mr. John H. Shamburger, and Mr. Jerald D. Broughton. Significant technical input and advice were provided by Mr. Richard B. Mercer, Dr. Jerome L. Mahloch, Mr. Douglas W. Thompson, and Dr. Larry W. Jones. The project was conducted under the general supervision of Dr. John Harrison, Chief, Environmental Effects Laboratory, Dr. Rex Eley, Chief, Ecosystem Research and Simulation Division, Mr. Andrew J. Green, Chief, Environmental Engineering Division and Mr. Norman R. Francingues, Chief, Treatment Processes Research Branch.

The guidance and support of Mr. Robert E. Landreth, Mr. Norbert B. Schomaker, and the Solid and Hazardous Waste Research Division, Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency are gratefully acknowledged. The Soils and Pavements Laboratory performed the physical testing under the direction of Mr. G. P. Hale. The Analytical Laboratory Group performed the chemical analyses under the direction of Mr. James D. Westhoff, Dr. Donald W. Rathburn and Mr. Jerry W. Jones. The diligent and patient efforts of Ms. Rosie Lott and Ms. Cherry Shaler, typists, and Mr. Jack Dildine, senior graphics coordinator, are gratefully acknowledged. Directors of WES during the course of this study were COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

SECTION 1

INTRODUCTION

Disposal on land is the oldest method of municipal solid waste disposal and is still the most widely used system. Over 90% of all municipal wastes are currently disposed of on land in open dumps or sanitary landfills. The sanitary landfill with systematic deposition, compaction and burial of refuse emerged in the 1930's as the safest, least objectionable system of land-based disposal. Some 1,400 cities are currently using landfills to dispose of some 318 thousand metric tons per day of solid wastes. The expenditure of money on solid waste disposal is surpassed only by that spent on schools and roads in most municipal budgets(1).

The disposition of solid wastes in landfills carries the inherent potential for degrading the quality of groundwater in the area of the landfill. There are numerous examples of municipal landfills producing groundwater pollution. Garland and Mosher(2) have cited several examples where the pollution from landfills could be detected; including one case where effects could be observed at a distance of 3 kilometers due to high selenium values in groundwater samples. Exler(3) reported that a landfill in Germany had a groundwater pollution plume that was also detectable for a distance of 3 kilometers down the flow gradient from the fill. The polluted groundwater in this case showed high levels of chloride and dissolved organic material.

The pollution of groundwater by landfills has in some cases caused severe degradation of drinking water supplies to the extent that such water is no longer potable. Incidences of pollution of this sort cause grave economic hardship on local governments that must attempt to relieve the pollution problem or provide a new water supply.

Some landfills are designed to contain all contaminants, but many allow the slow downward leakage of water that has come in contact with the buried refuse. This latter design anticipates the removal of undesirable materials in this leachate either by filtration through or adsorption onto the earth materials between the bottom of the landfill and the water table. This purification process is referred to as attenuation. The attenuated leachate that does reach the water table is then diluted by the much larger quantity of groundwater into which it flows. Groundwater pollution occurs when this filtration, adsorption and dilution process does not operate successfully.

Although some prediction of attenuation properties can be made from soil characteristics, such as clay content, particle size distribution, cation exchange capacity, etc., there is no conclusive method for verifying that attenuation is not effective until groundwater pollution is observed. The soil beneath a landfill should show an increase in contaminants if attenuation is occurring. Therefore, the examination of earth materials beneath sanitary landfills should be a useful technique for gauging the extent of pollutant attenuation.

The objectives of the present investigation are to examine three landfills that are situated in widely different geological circumstances in order to:

a) discover if changes have occurred in the chemical characteristics of local groundwater because of landfill operation,

b) determine the influence of the landfilled refuse on the chemical characteristics and physical properties of the geologic materials directly below the landfill,

c) determine if chemical constituents that are present in the soil below the landfill can be released into contacting water,

d) establish if a relationship exists between the depth below the refuse and the chemical and physical properties of the earth materials, and

e) discover if any physical or chemical characteristics of the material beneath a landfill can be used to predict the extent of contaminant attenuation.

To meet these objectives, an idealized concept or model (Figure 1) for leachate movement and attenuation was developed to provide a rationale for the sampling program. In this model the rainwater falling on the landfill saturates the refuse and then percolates through the soil directly below. A variable portion of the filterable and exchangeable material in the leachate is deposited in the soil below the landfill. This attenuated leachate continues downward into the water table. Groundwater flowing under the landfill dilutes the leachate and carries the pollutants in a plume down the groundwater gradient. Based on this idealized model, borings were located in such a way as to produce:

a) groundwater from wells beneath the landfill and from wells located both up and down the groundwater flow gradient in the area of the landfill,

b) samples of soil from beneath the landfill and from comparable depths outside the landfill,

c) soil samples collected at different levels down the boreholes both outside and beneath the landfill, and

d) samples collected near the top of the saturated zone (water table) around and inside the landfill.

Physical testing of soil samples collected below the landfill and at comparable depths outside the landfill was undertaken to evaluate changes related to the buried refuse. The physical characterization included percent

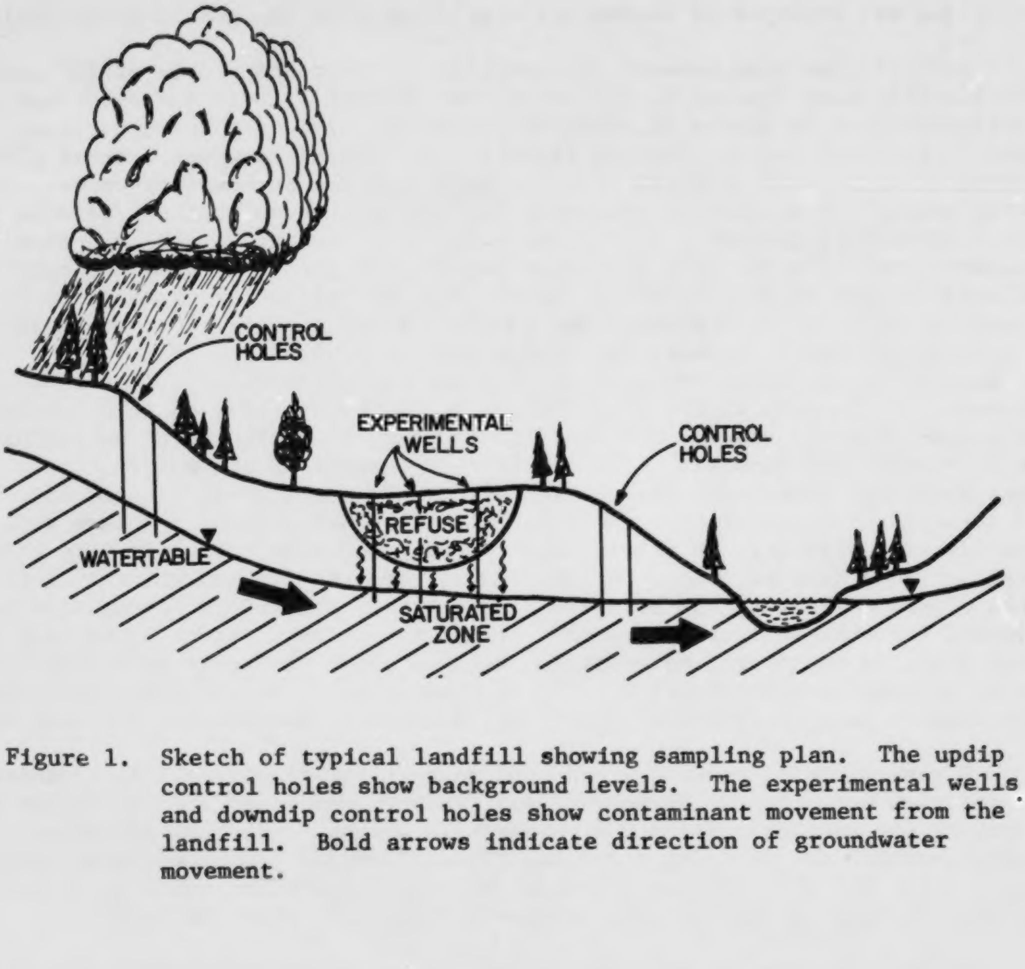

CONTROL HOLES
EXPERIMENTAL WELLS
CONTROL HOLES
REFUSE
WATERTABLE
SATURATED ZONE

Figure 1. Sketch of typical landfill showing sampling plan. The updip control holes show background levels. The experimental wells and downdip control holes show contaminant movement from the landfill. Bold arrows indicate direction of groundwater movement.

moisture, dry density, grain size distribution, permeability and soil classification. Randomization was used to test for significant differences in physical properties. Vertical variability in selected bore holes was also evaluated. The small sample sizes did not allow the use of statistical tests.

The samples of groundwater collected in this study were used to indicate loss of contaminants from the landfill or the soil beneath the landfill into the local groundwater. If contaminants are moving to the water table, their concentrations should be higher beneath and downdip from the landfill. A list of analyses run is given in Table 1. A one-way analysis of variance technique was employed to assess the significance of changes in water quality.

Soil samples from beneath the landfill and from comparable depths outside the landfill were treated in two ways: One aliquot of soil was extracted with distilled water to remove all ions that could be dislodged by water alone. A list of analyses run is given in Table 1. The distilled water extract gives a rate of release of material from the soil into the surrounding water. The water extract is assumed to represent the maximum concentration available in water contacting the soil, not the maximum, total amount capable of being leached from the soil. The distilled water leach then indicates the mobility of various ions being held in the soil. The most effective attenuation is occurring when the soil beneath the landfill shows an ability to accumulate a contaminant and to release the contaminant at a very slow rate. A randomization technique was used to test the significance of differences observed in the composition of the distilled water extracts of soil samples collected directly beneath the landfill and samples collected at comparable depth outside the landfill. The significant results of the randomization test point out those elements at each site whose mobility in aqueous solution is effected by material from the landfill. A second aliquot of fresh soil was digested with hot, 8N nitric acid to bring all ions not bound into silicate lattices into solution. A list of analyses run is also given in Table 1. This digest represents the total of all materials that could potentially be leached from the soil under the most severe conditions. Since it is assumed that there is no lateral movement of leachate above the water table, differences in composition between digests of these samples can be interpreted as the loss or gain of material in the soil due to the presence of the landfill.

A randomization technique was used to test for significant differences in composition between acid digests of soil samples collected directly below the landfill and samples collected at comparable depths (and above the water table) outside the landfill. The significant results from the randomization tests point out those elements at each site that are being added to the soil or removed from the soil by the movement of leachate from the landfill.

If the soil beneath the landfill is being altered by leachate from the landfill, any change should be most pronounced directly beneath the refuse and the magnitude of this change should decrease with depth. Samples of soil were taken at intervals down the boreholes to determine if any correlation between the concentration of materials in the soil and depth (or sample elevation) could be observed. Correlation with sample elevation was only attempted with those elements that had shown a significant contrast in concentrations available under and away from the landfill at each site. A

TABLE 1. CHEMICAL CONSTITUENTS ANALYTICALLY DETERMINED IN GROUNDWATER FILTRATES, DISTILLED WATER EXTRACTS, AND NITRIC ACID DIGESTS

Constituent	Groundwater filtrate	Water extract of soil samples	Nitric acid digests of soil samples
SO_4	X	X	--
SO_3	X	X	--
Cl	X	X	--
NO_3-N	X	X	--
NO_2-N	X	X	--
CN	X	X	--
TOC	X	X	--
Ca	X	X	--
Fe	X	X	X
Mg	X	X	--
Mn	X	X	X
Na	X	X	--
As	X	X	X
B	X	X	X
Be	X	X	X
Cd	X	X	X
Cr	X	X	X
Cu	X	X	X
Hg	X	X	X
Ni	X	X	X
Pb	X	X	X
Se	X	X	X
Zn	X	X	X

-- = Not determined.

Spearman rank correlation technique was employed. The correlation technique made it possible to see if consistent relationships could be observed between sample elevation and sample composition in borings made inside and outside the landfill.

Samples of soil collected near the top of the saturated zone both outside and inside the landfill were examined to see if any effects of lateral movement of leachate could be observed. Distilled water leaches and nitric acid digests of these soil samples were analyzed. Plots of analyses were prepared to assess any changes in constituents that could be related to the presence of the landfill. No attempt was made to evaluate these analyses statistically because of the small sample sizes involved.

SECTION 2

CONCLUSIONS

At all three municipal landfill sites, changes in the chemical composition of the groundwater could be related to the position of the borings with respect to the landfill. Water quality below and down the groundwater flow gradients from the landfills showed increased sulfate levels in every case. At several sites increased nitrate, total organic carbon, and cyanide levels could be related to the presence of the landfill.

No changes in physical parameters measured in soil samples in this study could be related to the effect of the landfill. No consistent alterations in dry density, water content, permeability, or percent fines could be related to the position of soil samples with respect to the landfill. Physical characteristics of sub-landfill soil samples as measured by standard engineering techniques were not significantly different from samples collected at comparable depth outside the landfill. No consistent vertical changes in soil physical characteristics in borings through the landfill could be detected. The percolation of leachate did not alter the permeability of the soil beneath the refuse. No evidence was found in this study to substantiate the idea that sub-landfill soils seal themselves.

Distilled water extracts prepared from soil samples showed all soluble constituents were present in very small quantities. Many variations observed were not consistent from one site to another. In general, there was more leachable sulfate, chloride, organic carbon, nitrate and more available trace metals in soil from under the landfills than in soils from similar depths outside the landfill. Calcium, iron and zinc were the only metals that showed decreased availability under any of the landfills. The lack of water-extractable iron under the landfill at the one actively operating site was probably due to its precipitation as an insoluble compound such as sulfide. In another series of distilled water extracts, many constituents showed decreasing availability with increasing sample depth in borings below the landfill, suggesting their source was the refuse in the landfill. Calcium and zinc were exceptions to this trend and showed increasing levels in distilled water extracts with increasing depth. This trend may be due to removal by leaching by organic acids from the refuse (especially in the case of calcium) or the formation of insoluble compounds under the landfill.

Analyses of distilled water extracts of soil samples taken from near the water table shows that the maximum concentration of many constituents as measured in the water extract can be displaced down the groundwater gradient from the landfill. Displacement of the concentration maxima was noted with nitrate, organic carbon, calcium, iron, magnesium, manganese, sodium and boron.

Nitric acid digests of soil show great variability in chemical composition. At two sites iron, manganese, boron, beryllium and zinc were found in higher concentrations in nitric acid digests from immediately under the landfill than at comparable depths outside the landfill. This suggests that these metals are being added to the soil under the landfill (i.e. attenuated). Only arsenic showed a decreased level under the landfills suggesting it was being mobilized or leached from the sub-landfill soil.

Analyses of nitric acid digests from soil samples collected at increasing depth below the landfill indicate that iron, manganese, arsenic, boron, beryllium, lead, selenium and zinc (at site B) are accumulating in soil immediately beneath the landfill. Only two metals, nickel and zinc (at site C), showed an increasing abundance with increasing depth indicating these metals are leaching out of the upper layers of sub-landfill soil.

Analyses of nitric acid digests of soil samples taken from near the water table also show that the maximum concentration of some of the landfill constituents can be displaced down the groundwater gradient from the landfill. This trend was noted for the maximum concentrations of arsenic, manganese, copper and lead.

The results of this investigation indicate that chemical characteristics, but not physical characteristics, were altered in soil under the landfill, and chemical changes in the sub-landfill soil can be related to the capacity of the soil to filter, absorb or precipitate the contaminants from the refuse. Instances were noted where the leachate added material to the soil and also mobilized normal soil constituents to effect changes in soil composition.

SECTION 3

RECOMMENDATIONS

The interaction between leachate from municipal refuse and soil is complex varying with the character of the soil and the composition of the leachate. The chemical character of the soil is itself changed as material is added or leached out. The landfill leachate varies with the nature of the refuse disposed and the type of decomposition occurring. The results of this survey indicate that significant chemical changes occur in the soil that can be related to the attenuation process.

Future investigations should include characterization of the landfill leachate before and after contact with the soil as well as analysis of acid digests of the soil. Any future study of sub-landfill soils should include soil variables such as mineralogy, cation exchange capacity, and slurry pH. Any continued work on leachate-soil interaction could include following soil changes through several annual cycles until stabilization of the refuse occurs. Further physical testing should be undertaken on a very fine scale, carefully including the soil-refuse interface.

Field investigations of this nature while involving many variables, represent the best approach to the understanding of how attenuation processes operate and their effect on groundwater quality. Continued work of this type may allow us to predict and overcome the hazard to groundwater resources involved in landfill disposal.

SECTION 4

METHODS AND MATERIALS

SITE SELECTION

Three municipal landfills were selected from widely different geographic areas in the Eastern United States. All sites were selected from areas where rainfall and infiltration rates were sufficient to produce an abundance of leachate. A summary of the important engineering and geologic characteristics of each of the sites selected for this survey is given in Table 2. The sites are designated only by letter.

Two principal factors effecting the character of the contaminants leaving a landfill are the nature of waste buried, and the age of material in the site. Other factors that impinge on the problem of the character of leachate from a landfill are oxidation-reduction conditions in the landfill, temperature in the landfill, and dilution of the leachate by local groundwater flow. The exact type and amount of waste material deposited in each site is difficult to determine, especially if the landfill has been completed and closed. Only in the case of site A is there a reasonably complete listing of wastes available from the local Department of Public Works (Table 3). Note that several types of industrial wastes have gone into this site including wastes from local rubber manufacturing, meat packing and paper mill operations. The information regarding the nature of waste placed at site B is not available. The waste is thought to be largely municipal (household and commercial) with only minor industrial input since there are no large manufacturing operations in the area served by the landfill. No waste survey is available for site C; but, engineering reports associated with the project state that the site received 900 tons per day of commercial and household refuse and 200 tons per day of incinerator ash. This site also received a great deal of sewage sludge and has been top-dressed with this material.

Sanitary landfill leachate typically changes in composition as the material in the landfill degrades (4,5) therefore the age of the landfill is an important consideration. Site A had been officially closed for fifteen years when the samples for this study were collected. However, there was some evidence of recent, unauthorized use of the site as an open dump for household refuse. The refuse was originally placed in trenches and was not compacted. Differential settling produced a series of shallow gullies where the trenches had been dug. The municipality later filled in the depressions with sewage sludge. At site B, the landfill was completed in 1972, and then regraded to produce a recreation area. The regrading included exposing and reburying part

TABLE 2. SUMMARY OF THE CHARACTERISTICS OF THE THREE SITES SELECTED FOR STUDY

Characteristic	Site A	Site B	Site C
Geographic area within the U.S.	North Central	South Central	East Central
General geologic setting	Glacial outwash (valley train deposits)	Wind-blown silt and clay (loess)	Deeply weathered residual soil (metamorphic terrane)
Mean annual rainfall	74 cm	124 cm	104 cm
Mean annual air temperature	$8^{o}C$	$19^{o}C$	$13^{o}C$
Nature of waste	Municipal and industrial	Municipal and industrial(?)	Municipal and industrial(?)
Liner used below refuse	None	None	None
Thickness of refuse observed	4.82-6.52 m (avg. 5.40 m)	1.92-4.88 m (avg. 3.08 m)	14.02-24.70 m (avg. 19.45 m)
Thickness of unsaturated zone	18.23-20.24 m (avg. 19.33 m)	0.91-3.51 m (avg. 2.47 m)	0.91-10.88 m (avg. 4.79 m)
Nature of material in unsaturated zone	Sand	Clayey silt	Silty sand
Average hydraulic conductivity below refuse	$1x10^{-1}$ cm/sec	$7.3x10^{-7}$ cm/sec	$2.9x10^{-5}$ cm/sec
Average thickness of covering material	1.65 m	0.09 m	0.82 m
Character of covering material	Sand and gravel	Clay	Clay
Dates of operation of site	1947 - 1961	1959 - 1972	1964 - present
Type of operation	Trench and fill	Surface fill	Surface fill

TABLE 3. CHARACTER OF WASTE DEPOSITED IN LANDFILL AT SITE A AS LISTED BY THE MUNICIPALITY

- Mixed demolition refuse
  - Sand
  - Dirt
  - Gravel
  - Rock
  - Broken pavement
  - Construction materials

- Household refuse
  - Domestic garbage and kitchen wastes
  - Domestic incinerator residue
  - Cans and glass bottles
  - Furniture and carpets
  - Major appliances

- Yard refuse
  - Logs
  - Grass and garden clippings
  - Brush
  - Chipped limbs and leaves

- Commercial refuse
  - Used tires
  - Mixed commercial trash
  - Kitchen wastes
  - Commercial incinerator residue
  - Scrap metal
  - Wood crates

- Industrial wastes
  - Rubber manufacturing wastes
  - Rubber scrap
  - Liquid and wet chemical waste
  - Paper mill sludge
  - Oil, tar and asphalt
  - Meat packing waste
  - Paunch
  - Manure
  - Sewage grit
  - Sewage sludge

of the refuse and compacting the landfill prior to partial paving with asphalt. The regrading took place only a year before this investigation. Site C was still receiving wastes; but, the portion where two of the borings (1 and 2) were placed had been closed from one to three years at the time of sampling.

All of the sites selected had been in place long enough to have possibly effected the groundwater and soil beneath and around the landfill (see Table 2). All of the sites contain domestic and commercial wastes; but only site A has received a major amount of industrial waste. These landfills were chosen because they have many factors in common with other landfills in the Eastern United States. All contain mixed residential and commercial refuse buried using prevailing landfilling methods.

SAMPLING PROCEDURES

A general sampling plan for all sites was generated using the theoretical model as described above (Figure 1) and then modified to fit the requirements at the individual sites. The general sampling scheme called for six or more holes to be bored at each landfill: a minimum of two holes to be bored through the buried refuse and five to six holes to be bored outside the landfill. This sampling pattern allowed comparison between typical, uneffected groundwater and soil, and groundwater and soil which was in contact with leachate draining from the buried refuse.

All sampling was done with a truck-mounted, rotary drill using 16.8 cm OD hollow-stem auger. The auger with a central plug in place was drilled in to the desired depth. The central plug was removed and a Hvorslev fixed-piston sampler (Figure 2) or a split spoon sampler (Figure 3) was pressed into the sediment or soil directly below the end of the auger using the hydraulic cylinders on the drill rig. In this way an undisturbed soil or sediment sample was obtained. The split spoon sampler was only used in cases where objects were encountered in the subsurface that could not be penetrated by the thin-walled tube (Shelby tube) on the Hvorslev sampler.

The vertical distribution of soil/sediment samples collected down the hole was arranged in a way to maximize the probability of collecting samples at two critical points in the boring: the refuse-soil interface, and the top of the saturated zone. Since the strongest effects of leachate on the subfill material should occur directly below the refuse, a sample was always taken at the depth predicted by the landfill design as being the combined thickness of the refuse and cover. Sampling then continued at closely spaced intervals down the hole. The top of the water-saturated zone was predicted from water table measurements that had been recorded for other wells in the area. A series of closely spaced samples was taken in this interval. The holes were allowed to remain open for two to three days with the auger flights in place. These auger flights served as a temporary well casing to prevent seepage from the surface from entering the well. Groundwater samples were obtained from the temporary wells by lowering a bailer into the top of the hollow stem auger. After a groundwater sample was obtained the auger was removed and the holes were backfilled with cement and/or bentonite to a point well above the water table. The filling was then completed with well cuttings. This

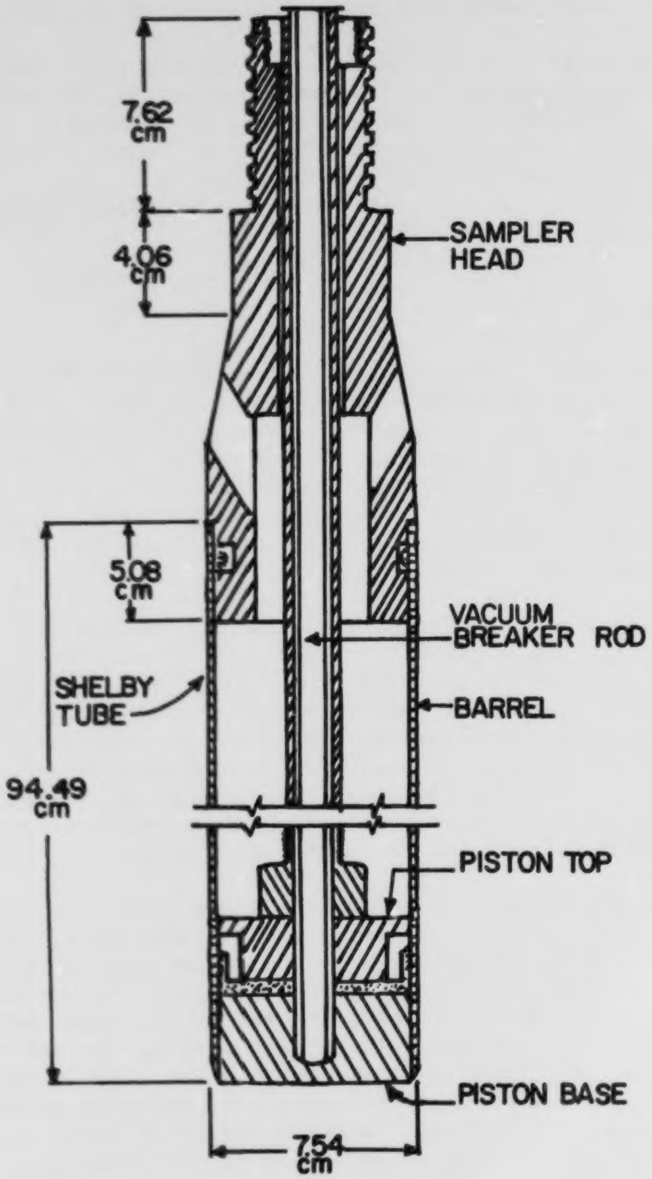

7.62 cm
4.06 cm
SAMPLER HEAD
5.08 cm
VACUUM BREAKER ROD
SHELBY TUBE
BARREL
94.49 cm
PISTON TOP
PISTON BASE
7.54 cm

Figure 2. Sketch of Hvorslev Sampler

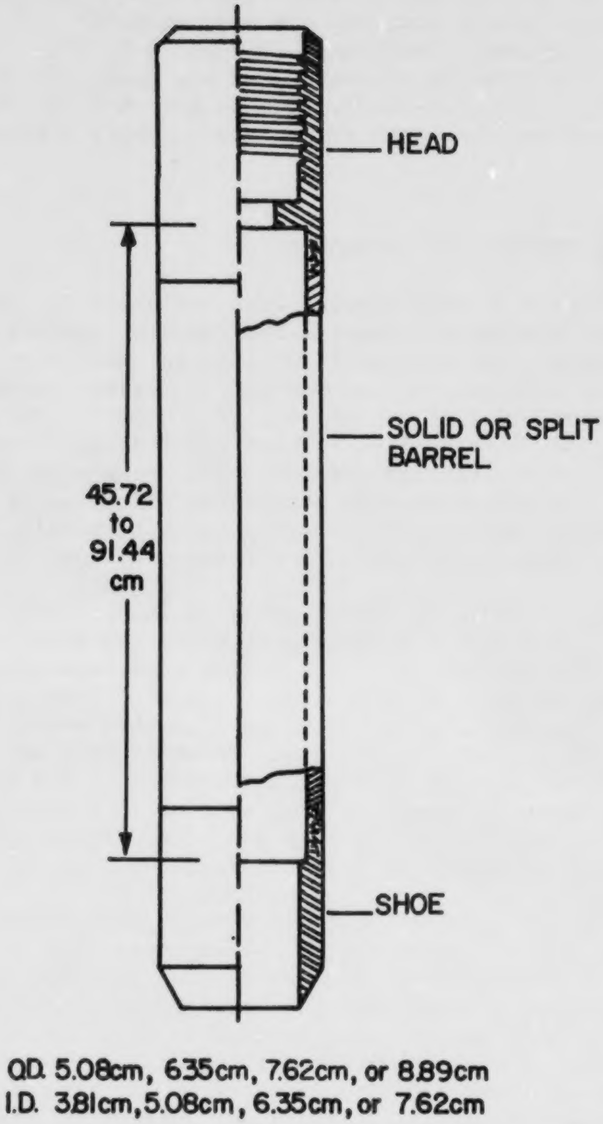

HEAD
SOLID OR SPLIT BARREL
45.72 to 91.44 cm
SHOE
O.D. 5.08cm, 6.35cm, 7.62cm, or 8.89cm
I.D. 3.81cm, 5.08cm, 6.35cm, or 7.62cm

Figure 3. Sketch of split spoon sampler.

was done to assure that a well would not provide a conduit for flow of polluted water to the water table.

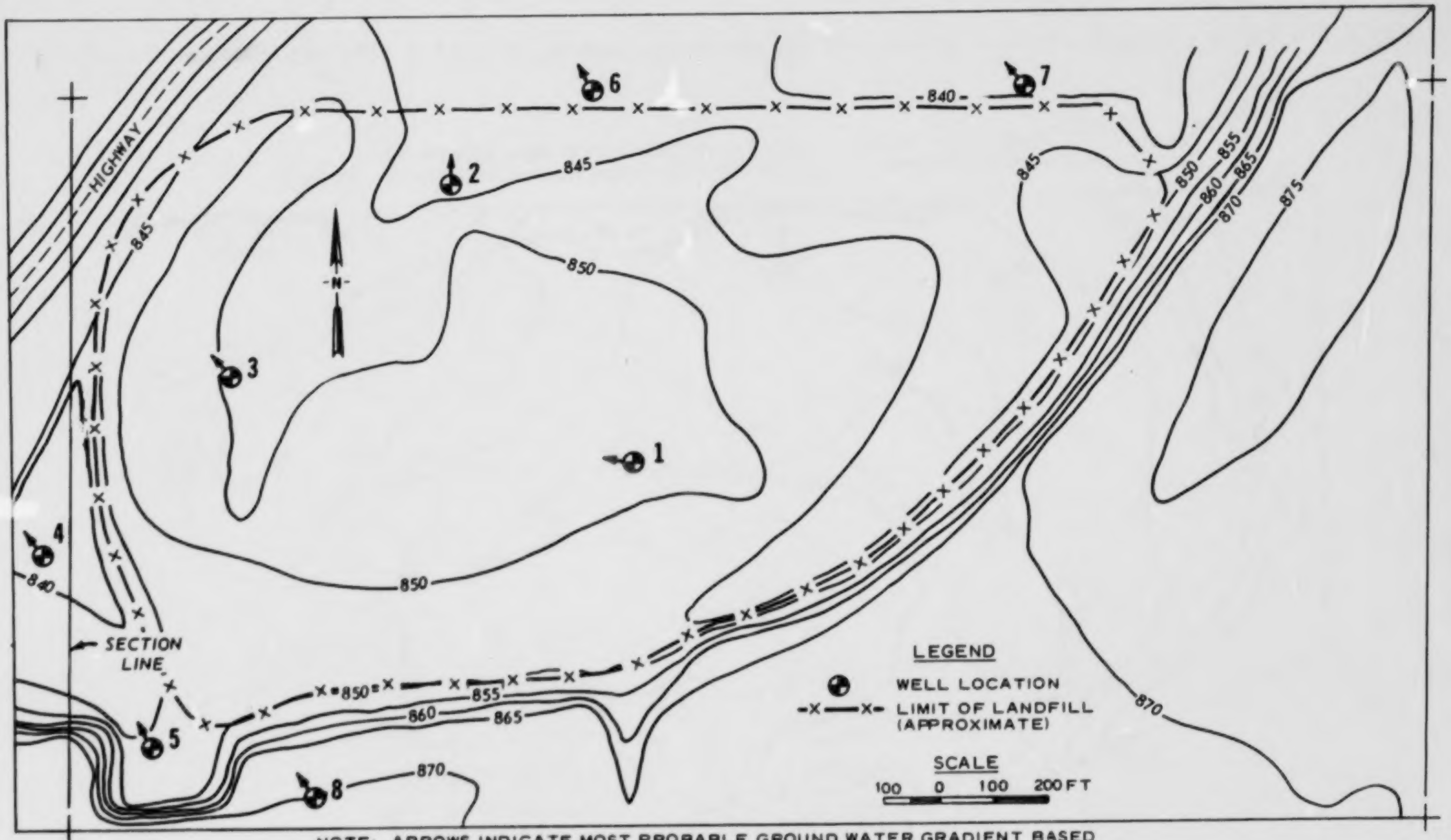
The locations of all borings at each landfill site are given in Figures 4-6. Arrows in these figures indicate the most probable direction of groundwater flow deduced from water level maps (Figures A-1, B-1, C-1 in appendices) and chemical data. The descriptive well logs are presented in the appendices (Tables A-1--A-8, B-1--B-8, C-1--C-9). Tables A-9, B-9, and C-10 list all soil/sediment samples examined from each boring giving their elevation and other relevant data.

SAMPLE HANDLING AND PREPARATION TECHNIQUES

Two different types of soil samples were collected in the boring program: samples for physical testing and samples for chemical analysis. Groundwater samples were also taken from each well for chemical analysis. The set of samples obtained for physical testing was used to determine soil class under the unified soil classification system (6), dry density, grain-size distribution, water content and permeability. These physical parameters were determined using standard engineering test procedures. This sample set was collected without disturbing the soil more than necessary. All physical testing samples were carefully packaged and sealed in coring tubes to retain the original moisture content and sample texture during transportation.

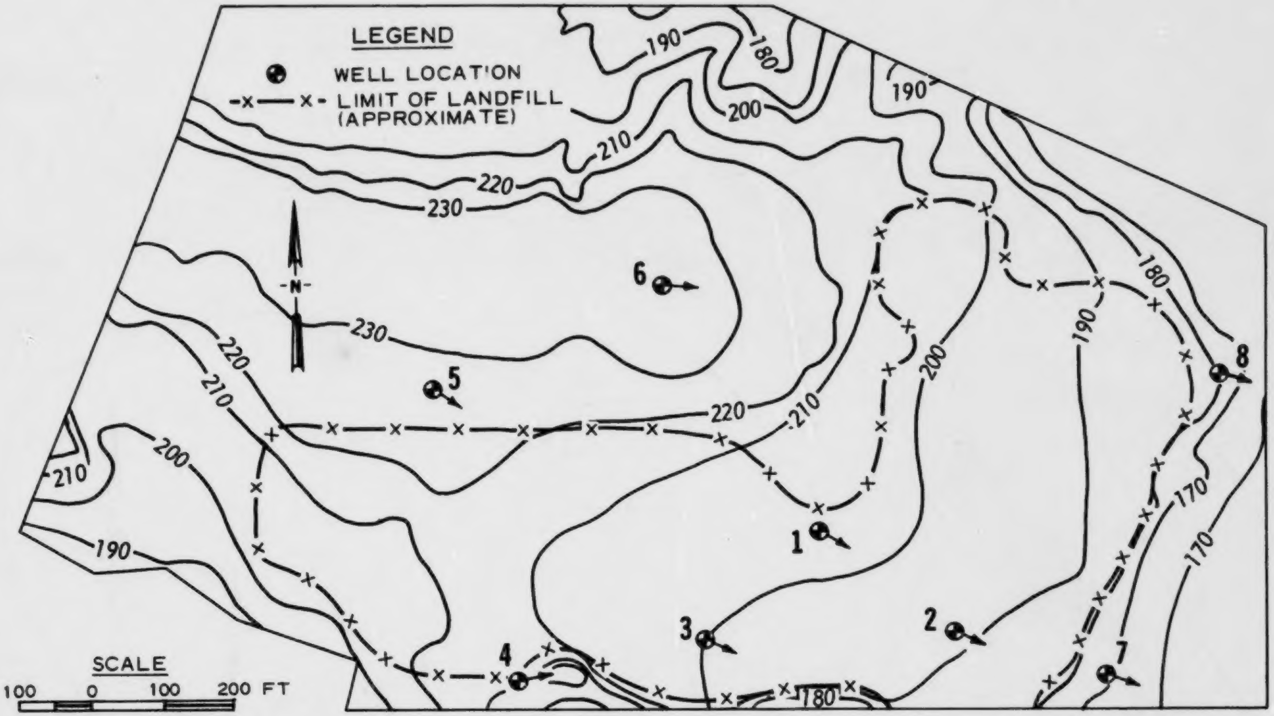
Depth to groundwater was measured with a chalked, steel tape at each boring. All of the groundwater samples were collected from the borings by bailing the water from the center of the hollow stem auger using a bailer made from small diameter tubing. The groundwater was transferred to polyethylene bottles which were labelled and packed in an insulated chest filled with crushed ice. The samples were stored under refrigeration and kept tightly capped until they were prepared for chemical analysis. The preparation consisted of centrifuging each sample at 2200 rpm for 30 minutes. The resulting supernatant was membrane-filtered through a 0.45 nm filter and split into five subsamples which were preserved as shown in Table 4.

Samples of soil for chemical analysis were collected simultaneously with the samples for physical testing; but, no attempt was made to maintain the soil in an undisturbed condition. Each sample was removed from the sampler, placed in a wide-mouthed polyethylene bottle, labelled, and packed in an ice-filled chest. These soil samples were refrigerated during all subsequent transportation and/or storage. Two extracts were made from each soil sample: one with distilled water and one with 8N nitric acid. The material that could be easily leached out with distilled water was considered transient and would readily be leached from the soil by dissolution in rainwater. The nitric acid leach would contain the transient materials and also all of the material that could be solubilized by a strong, oxidizing acid. Those elements present as carbonates or sulfides, or adsorbed to clay minerals, to iron oxide or to insoluble organic materials would be freed (7,8). Elements in non-clay silicate lattices would be leached only to a minor degree (9).


HIGHWAY
SECTION LINE
N
1
2
3
4
5
6
7
8
840
845
850
855
860
865
870
875
LEGEND
WELL LOCATION
-X——X- LIMIT OF LANDFILL (APPROXIMATE)
SCALE
100 0 100 200 FT

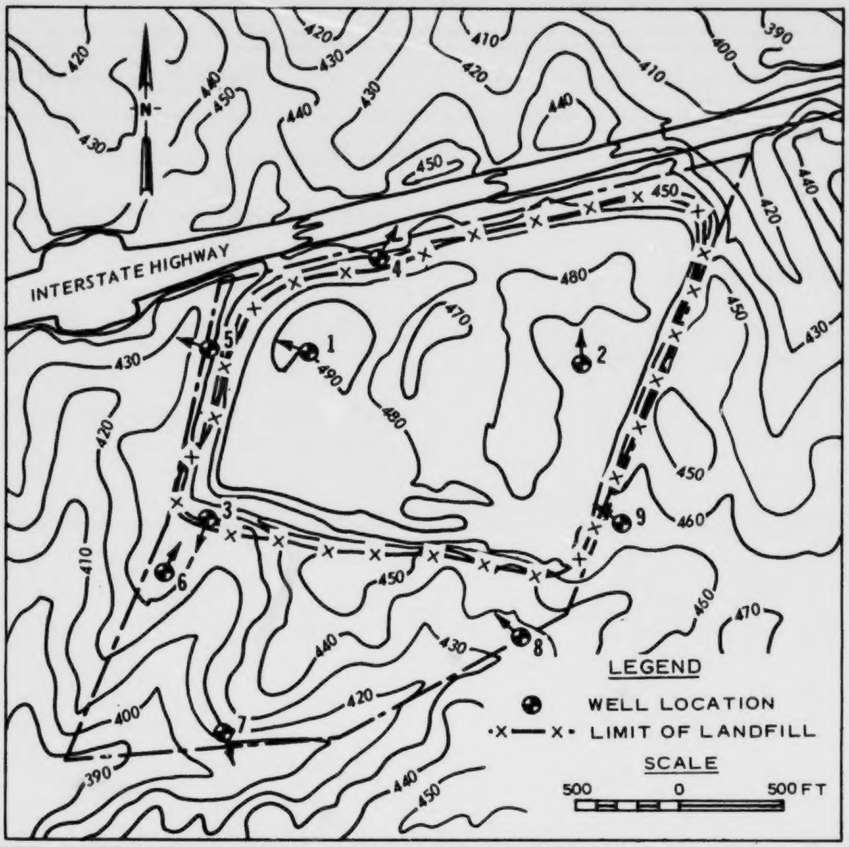
NOTE: ARROWS INDICATE MOST PROBABLE GROUND WATER GRADIENT BASED ON WATER TABLE MEASUREMENTS AND CHEMICAL ANALYSES.

Figure 4. Topographic map of site A (contour lines are in feet above mean sea level). 0.305 m = 1 ft.


LEGEND
WELL LOCATION
-x——x- LIMIT OF LANDFILL (APPROXIMATE)
-N-
SCALE
100 0 100 200 FT
170
180
190
200
210
220
230
1
2
3
4
5
6
7
8

NOTE: ARROWS INDICATE MOST PROBABLE GROUND WATER GRADIENT BASED ON WATER TABLE MEASUREMENTS AND CHEMICAL ANALYSES.

Figure 5. Topographic map of site B (contour lines are in feet above mean sea level). 0.305 m = 1 ft.


N
INTERSTATE HIGHWAY
420
430
440
450
420
430
430
440
410
420
410
400
390
440
450
450
440
420
450
430
480
470
490
480
430
420
410
450
460
450
460
470
440
430
420
400
390
440
450
1
2
3
4
5
6
7
8
9
LEGEND
WELL LOCATION
•X——X• LIMIT OF LANDFILL
SCALE
500
0
500 FT

NOTE: ARROWS INDICATE MOST PROBABLE GROUND WATER GRADIENT BASED ON WATER TABLE MEASUREMENTS AND CHEMICAL ANALYSES.

Figure 6. Topographic map of site C (contour lines are in feet above mean sea level). 0.305 m = 1 ft.

TABLE 4. METHODS OF PRESERVATION OF WATER EXTRACTS AND FILTERED GROUNDWATER SUBSAMPLES FOR CHEMICAL ANALYSIS

Chemical species to be determined	Method of preservation
SO_4, SO_3, Cl, NO_3, NO_2	Refrigeration to 4°C
CN	Sample brought to pH 11 with NaOH
Total organic carbon	Refrigeration to 4°C
Ca, Fe, Mg, Mn, Na, As, B, Be, Cd, Cr, Cu, Ni, Pb, Se, Zn	Samples acidified with HCl to pH 1
Hg	$KMnO_4$ added and samples acidified with HNO_3 to pH 1

For distilled water extracts, the contents of each sample bottle was mixed to assure a homogeneous sample. A 200-gram subsample of moist soil was weighed out into a 1000-ml polycarbonate centrifuge bottle and six hundred ml of distilled-deionized water was added to each. The centrifuge bottles were shaken on a rotary shaker for one hour, and then centrifuged at 2200 rpm for 30 minutes. The supernatant was filtered through a 0.45 nm membrane filter. The filtrate was split into five subsamples for chemical analysis. The subsamples were preserved as outlined in Table 4.

A second subsample consisting of 50 grams of moist soil was taken from each sample bottle for nitric acid digestion. In each digestion the soil was weighed into a 250-ml fluorocarbon beaker and 60 ml of 8N reagent grade nitric acid was added. The soil-acid suspension was heated to 95°C for 45 minutes and stirred every fifteen minutes. After cooling to room temperature, the suspension was filtered through a 0.45 nm membrane filter. The digested soil was washed in the filter three times with 20-ml portions of 8N nitric acid. The filtrate was quantitatively transferred to a 250-ml volumetric flask and brought up to volume with 8N nitric acid and then stored in a polyethylene bottle. No preservation procedure was necessary.

A third subsample was taken from each sample bottle to determine the moisture content of the soil. These moisture contents were used to correct subsequent chemical analyses so that soil acid digests could be expressed in milligrams per kilogram dry weight of soil.

PHYSICAL TESTING METHODS

The physical tests run on these samples included water content, sample dry density, permeability, and grain-size analysis. Data gathered from these tests and visual examination of the samples were used to classify the materials into standard soil engineering categories. All testing was done using standard soil engineering methods (10).

To determine water content, a sample taken from a sealed coring tube was weighed into a tared sample dish, dried at 110°C and weighed periodically until a constant weight was obtained.

Sample dry density (or dry unit weight) is the weight of oven-dried soil per unit volume of soil. This measurement can be made in two different ways: by trimming the soil sample into a precisely measured regular shape and drying and weighing the trimmed sample; or, by sealing the surface of a soil specimen with wax and measuring its volume by water displacement, then removing the sealing material and drying and weighing the specimen. The water displacement procedure was used with samples containing gravel or other coarse material that prevented the sample from being trimmed accurately.

Grain-size analysis was performed by sieving the dried, disaggregated soil through a standard sieve series. Standard hydrometer density measurements were run on a suspension prepared from the fraction passing the 200-mesh sieve.

Permeability measurements were made using a constant-head test system with coarse-grained soils, and a falling-head test system with fine sands or clays. In all cases standard procedures and equipment were employed (10).

The major characteristics (especially grain-size analyses and characteristics of the fine fraction) of the samples were used to classify the soils. The classification system is summarized in Table 5. These classification categories and symbols are used to summarize soil characteristics in the logs presented in Tables A-1--A-8, B-1--B-8, and C-1--C-9.

CHEMICAL ANALYTICAL METHODS

The techniques used in analyzing the filtered groundwater samples, distilled water extracts and nitric acid digests are summarized in Table 6. In all cases, the samples were run within the recommended time limits for the storage of samples (11).

The analyses of groundwater samples is given in milligrams per liter of filtered sample. The water extracts are also presented in milligrams per liter of filtered extractant. The water extract represents an equilibrium or near equilibrium solution with respect to the solid phases and the adsorbed phases in the soil; therefore, the analytical data are presented on a solution basis rather than a dry weight basis. The nitric acid digests are a determination of the total acid digestible fraction; therefore, the results are presented as milligrams extracted per kilogram dry weight of soil.

TABLE 5. DESCRIPTIONS OF USCS SOIL GROUPS (6)

Group symbol	Typical group description
GW	Well-graded (poorly-sorted) gravels, gravel-sand mixtures, little or no fines
GP	Poorly-graded (well-sorted) gravels, or gravel-sand mixtures, little or no fines
GM	Silty gravels, gravel-sand-silt mixtures
GC	Clayey gravels, gravel-sand-clay mixtures
SW	Well-graded (poorly-sorted) sands, gravelly sands, little or no fines
SP	Poorly graded (well-sorted) sands, gravelly sands, little or no fines
SM	Silty sands, sand-silt mixtures
SC	Clayey sands, sand-clay mixtures
ML	Inorganic silts, very fine sands, clayey silts, low plasticity
CL	Inorganic clays, low to medium plasticity, lean clays
OL	Organic silts and organic silty clays of low plasticity
MH	Inorganic silts, micaceous or diatomaceous fine, sandy or silty soils, elastic silts
CH	Inorganic clays of high plasticity, fat clays
OH	Organic clays of medium to high plasticity, organic silts
Pt	Peat and other highly organic soils

TABLE 6. TECHNIQUES USED IN THE ANALYSIS OF DISTILLED WATER EXTRACTS, NITRIC ACID DIGESTS AND GROUNDWATER FILTRATES

Chemical species	Procedures and/or instrumentation*	Lowest reporting* concentration in (ppm)
SO_4	Standard Turbidimetric Method[+] in combination with a Varian Model 635 Spectrophotometer	8
SO_3	Standard Potassium Iodide-Iodate Titration method[+]	1
Cl	Standard Mercuric Nitrate Titration method[+]	5
NO_3-N	Technicon II Auto Analyzer, Industrial Method no. 100-70W[±]	0.01
NO_2-N	Same as above	0.01
CN	Technicon II Auto-Analyzer, Industrial Method no. 315-74W[±]	0.01
TOC	Determined with Envirotech Model No. DC 50 TOC Analyzer	1
Ca	Determined with a Spectrametrics Argon Plasma Emmission Spectrophotometer Model II	0.03
Fe	Same as above	0.05
Mg	Same as above	0.03
Mn	Same as above	0.03
Na	Same as above	0.03
As	Determined with a Gaseous Hydride System, Perkin-Elmer Atomic Absorption Unit	0.001
B	Determined with a Spectrametrics Argon Plasma Emission Spectrophotometer Model II	0.02

(continued)

TABLE 6 (continued)

Chemical species	Procedures and/or instrumentation*	Lowest reporting concentration in (ppm)
Be	Same as above	0.02
Cd	Same as above	0.03
Cr	Same as above	0.03
Cu	Same as above	0.02
Hg	Determined with a Nisseisangyo Zeeman Shift Atomic Absorption Spectrophotometer	0.0002
Ni	Determined with a Spectrametrics Argon Plasma Emission Spectrophotometer Model II	0.03
Pb	Same as above	0.1
Se	Determined with a Perkin-Elmer Heated Graphite Atomizer Atomic Absorption Unit	0.002
Zn	Determined with a Spectrametrics Argon Plasma Emissions Spectrophotometer Model II	0.03

* Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

+ Standard Methods for the Examination of Water and Wastewater, American Public Health Association, New York, 13th Edition, 1971.

± Technicon Industrial Systems, Tarrytown, New York.

SECTION 5

RESULTS AND DISCUSSION

PHYSICAL TESTING

The soil parameters measured in the physical testing program are those most likely to be effected by the infiltration of leachate from overlying refuse. The literature indicates that the leachate suspension is filtered by the uppermost layer of soil below the refuse (4). Filtration of the leachate should cause the soil to show:

a) an increase in density due to the addition of fine material in intergranular spaces,

b) a decrease in permeability due to accumulation of fine-grained particles that obstruct the natural pore connections in the soil,

c) an increase in the percentage of fine silt- and clay-sized material (less than 200-mesh grain size) due to accumulated leachate residue, and

d) a change in water content due to the accumulation of water retaining organic material.

A complete tabulation of data obtained from the physical testing program is given in Tables 7, 8 and 9. A summary contrasting the physical characteristics found in the samples from directly below the landfill and at comparable elevations outside the landfill is given in Table 10. None of the sites show significant differences in dry density between soil beneath and outside the landfill. Likewise, the variation in water content shows no pattern that can be related to the position of the sample with respect to the landfill. The data available on permeability or hydraulic conductivity do show a significant difference between inside (sub-refuse) and outside samples for site B. Unfortunately, it is very difficult to obtain reliable, reproducible permeability measurements from this extremely fine-grained, loess-based soil. Laboratory experiments with reconstituted samples indicated that the permeability is very dependent on the state of compaction of the material. Slight disturbances of the samples could account for a great deal of the variation observed or the differences might have been produced by the grading and compaction when the completed fill was developed as a recreation area. There is no significant difference in the weight percentage of material finer than 200-mesh for samples under and outside the landfills at any of the three sites. If the residue from leachate is being trapped, it constitutes a very small portion of the cored sample.

TABLE 7. PHYSICAL TESTING DATA FOR SAMPLES FROM SITE A

Boring no.	Sample no.	Depth (m)	Dry density (g/cc)	Water content (%)	Permeability or hydraulic cond. (cm/sec)	Classification
1	P1	7.20 - 7.70	1.60	4.1	1.1×10^{-1}	Sand (SP), brown
1	P4	10.94 - 11.64	1.62	3.1	1.1×10^{-1}	Sand (SP) with trace gravel, brown
1	P6	22.65 - 22.84	1.59	3.9	1.4×10^{-1}	Sand (SP) with trace gravel, brown
2	P1	6.25 - 6.68	1.61	3.6	0.58×10^{-1}	Sand (SP) with trace gravel, brown
2	P2	6.92 - 7.44	1.72	3.3	--	Gravelly sand (SP), brown
2	P3	8.81 - 9.42	1.64	2.9	1.1×10^{-1}	Sand (SP) with gravel, brown
2	P4	13.87 - 14.39	1.50	6.7	0.47×10^{-1}	Sand (SP), brown
2	P5	19.51 - 19.87	1.55	3.8	0.76×10^{-1}	Sand (SP) with gravel, brown
2	P6	24.39 - 24.94	1.56	3.8	--	Sand (SP) with trace gravel, brown
3	P1	7.86 - 8.32	1.63	5.2	0.82×10^{-1}	Sand (SP) with gravel, brown
3	P3	10.82 - 11.25	1.61	2.5	1.1×10^{-1}	Sand (SP) with trace gravel, brown
3	P5	22.25 - 22.53	1.76	2.4	1.3×10^{-1}	Gravelly sand (SP), brown
4	P1	3.20 - 3.90	1.59	7.5	2.0×10^{-1}	Sand (SP), brown
4	P3	6.25 - 6.62	1.59	4.0	--	Sand (SP), brown
5	P1	4.57 - 5.29	1.65	2.8	--	Sand (SP) with gravel, brown
5	P3	7.62 - 8.20	1.67	2.9	--	Sand (SP) with gravel, brown
5	P5	18.44 - 18.83	1.74	2.7	--	Sand (SP) with gravel, brown
6	P1	4.72 - 5.33	1.57	2.8	--	Sand (SP) with gravel, brown
6	P3	7.77 - 8.42	1.71	3.2	--	Sand (SP) with gravel, brown
6	P5	19.00 - 19.48	1.69	2.9	--	Sand (SP) with gravel, brown
7	P1	4.42 - 4.76	1.62	3.3	--	Sand (SP) with trace gravel, brown
7	P3	7.77 - 8.26	1.78	3.1	--	Gravelly sand (SP), brown
7	P4	13.26 - 13.75	1.75	2.9	--	Sand (SP) with gravel, brown
8	P1	14.32 - 15.03	1.64	4.5	--	Sand (SP) with trace gravel, brown
8	P3	17.38 - 17.96	1.66	3.4	--	Sand (SP) with gravel, brown
8	P5	28.65 - 28.99	1.70	4.2	--	Sand (SP) with gravel, brown

Note: -- indicates no data available.

TABLE 9. PHYSICAL TESTING DATA FOR SAMPLES FROM SITE B

Boring no.	Sample no.	Depth (m)	Density (g/cc)	Water content (%)	Permeability or hydraulic cond. (cm/sec)	Classification
1	P1	6.25 - 6.37	--	26.7	--	Silt (ML) gray
1	P2	8.41 - 8.87	1.48	33.3	7.72×10^{-8}	Silty clay (CL) gray
2	P2	3.66 - 4.15	1.57	24.7	8.41×10^{-7}	Silt (ML) grayish brown
2	P3	5.79 - 6.52	1.56	28.8	6.22×10^{-7}	Silt (ML) grayish brown
6	P1	6.10 - 6.77	1.40	20.1	7.72×10^{-5}	Silt (ML) brownish tan
6	P3	9.15 - 9.85	1.57	30.3	3.24×10^{-6}	Silt (ML) grayish brown
7	P3	4.57 - 5.27	1.53	28.9	7.84×10^{-6}	Silt (ML) brownish gray
8	P1	6.10 - 6.68	--	32.5	--	Silt (ML) olive gray

Note: -- indicates no data available.

TABLE 9. PHYSICAL TESTING DATA FOR SAMPLES FROM SITE C

Boring no.	Sample no.	Depth (m)	Dry density (g/cc)	Water content (%)	Permeability or hydraulic cond. (cm/sec)	Classification
1	P1	25.91 - 26.36	1.53	18.5	6.6×10^{-5}	Sandy silt (ML), brown
1	P3	28.96 - 29.40	1.71	17.3	7.8×10^{-5}	Silty sand (SM), brown
2	P1	18.29 - 18.96	1.65	19.4	6.6×10^{-5}	Silty sand (SM), brown
2	P3	22.26 - 22.59	1.66	18.9	2.8×10^{-4}	Sandy silt (ML), brown
3	P1	19.97 - 20.46	1.69	21.1	1.2×10^{-6}	Clayey, sandy silt (ML), brown
3	P3	22.47 - 22.92	1.69	18.1	2.9×10^{-5}	Sandy silt (ML), brown
4	P1	1.70 - 2.03	1.52	28.9	3.0×10^{-7}	Clayey, sandy silt (ML), brown
4	P4	8.49 - 8.76	1.64	21.2	5.7×10^{-6}	Sandy silt (ML), brown
6	P2	0.91 - 1.46	1.63	16.4	5.9×10^{-5}	Clayey, sandy silt (ML), tan
6	P4	4.57 - 5.11	1.78	14.9	1.9×10^{-5}	Sandy silt (ML), brown
7	P2	0.91 - 1.58	1.52	20.3	4.3×10^{-5}	Sandy silt (ML), reddish brown
9	P4	7.32 - 7.88	1.69	19.2	1.7×10^{-5}	Silty sand (SM), brown

TABLE 10. COMPARISON OF THE PHYSICAL PROPERTIES OF THE UPPERMOST SAMPLES COLLECTED WITHIN AND OUTSIDE THE LANDFILLS

Sample	Location (inside/outside)	Dry density (gm/cc)	Water content (%)	Permeability (cm/sec)	Weight % finer than 200 mesh
A 1P1	inside	1.60	4.1	1.1×10^{-1}	<2%
A 2P1	inside	1.61	3.6	0.58×10^{-1}	<2%
A 3P1	inside	1.63	5.2	0.82×10^{-1}	<2%
A 4P1	outside	1.59	7.5	--	<2%
A 5P1	outside	1.65	2.8	--	<2%
A 8P1	outside	1.64	4.5	--	<2%
A 6P1	outside	1.57	2.8	--	<2%
A 7P1	outside	1.62	3.3	--	<2%
B 1P2	inside	1.48	33.3	7.72×10^{-8}	99%
B 2P2	inside	1.57	24.7	8.41×10^{-7}	99%
B 6P1	outside	1.40	20.1	7.72×10^{-5}	99%
B 7P3	outside	1.53	28.4	7.84×10^{-6}	96%
C 1P1	inside	1.53	18.5	6.6×10^{-5}	64%
C 2P1	inside	1.65	19.4	6.6×10^{-5}	44%
C 3P1	outside	1.69	21.1	1.2×10^{-6}	66%
C 4P1	outside	1.52	28.9	3.0×10^{-7}	82%
C 6P2	outside	1.63	16.4	5.9×10^{-5}	52%
C 7P2	outside	1.52	20.3	4.3×10^{-5}	58%

In each boring under the landfill a series of samples were taken at increasing depth. Again, no consistent pattern could be observed relating the physical characteristics to the depth (or elevation).

None of the physical tests with the possible exception of permeability measurements at site B showed any consistent differences between samples taken directly under the landfill and those taken outside the landfill. No consistent pattern could be found in samples taken at differing depths in the same borings under the landfills. Any differences which do occur apparently are confined to a narrow range immediately at the interface between the refuse and the soil. Detection of these would probably require examination of a core through this interface region in very fine detail. None of the usual engineering tests demonstrated any effects which could be attributed to attenuation.

CHEMICAL ANALYSES OF GROUNDWATER

The goal of the groundwater investigation is to determine if changes in chemical parameters observed in different borings at each site could be related to the position of the boring with regard to the landfill and the direction of groundwater movement. A survey of the literature suggests that of the chemical parameters measured those most likely to indicate contamination from leachate in the groundwater are sulfate, chloride, total organic carbon, calcium, iron, magnesium, manganese and sodium (2,3). The minor and trace elements appearing in the groundwater around a landfill vary widely depending on the concentrations present in the waste at a particular landfill.

The tabulation of groundwater analyses obtained from wells at sites A, B and C are presented in Tables 11-13. The data are divided into three groups for each site; those up the groundwater gradient from the landfill, those under the landfill and those down the groundwater gradient from the landfill. The three groups of samples at each site show different means for the parameters measured and initial statistical analysis indicated widely different variances. Because of these inhomogeneous variances, the restricted number of samples in each group, and the large number of determinations that fall below the limits of detection, a non-parametric (distribution-free) analysis of variance techniques was used to determine if differences between means of parameters measured were significant. The statistical technique employed was the Kruskal-Wallis one-way analysis of variance (12,13). This test requires only that data have an underlaying continuous distribution and that the data can be ranked. This test does not require that the data have a normal distribution or be homogeneous with regard to variance. Because of the differences in numbers of samples at different sites, two different levels of significance (95.4% and 96.8%) were used.

The analysis of variance results are given in Table 14. Strong influence of the type of geologic material at each site is evident in the differences in background levels of metals present. Site A was underlain by clean glacial outwash consisting primarily of quartz sand. The upgradient groundwater

TABLE 11. CHEMICAL COMPOSITION OF GROUNDWATER OBTAINED FROM BORINGS AT LANDFILL A

	Up groundwater gradient			Under landfill			Down groundwater gradient	
Parameters	Boring 4	Boring 5	Boring 8	Boring 1	Boring 3	Boring 2	Boring 6	Boring 7
SO_4	<8	<8	<8	25	47	23	26	35
SO_3	<1	<1	<1	<1	<1	<1	<1	<1
Cl	<5	<5	<5	5	5	5	5	5
NO_3-N	<0.01	<0.01	<0.01	0.38	0.02	<0.01	<0.01	<0.01
NO_2-N	<0.01	<0.01	<0.01	0.09	0.03	0.04	0.04	0.03
CN	<0.01	<0.01	<0.05	<0.01	0.01	<0.01	<0.01	<0.01
TOC	<1	<1	<1	21	48	50	20	27
Ca	<0.03	<0.03	<0.03	34.3	69.0	127.0	35.0	35.5
Fe	<0.05	<0.05	<0.05	3.5	10.5	18.6	22.0	22.0
Mg	<0.03	<0.03	<0.03	17.10	48.50	39.50	35.00	35.50
Mn	<0.03	<0.03	<0.03	3.2	3.0	4.9	8.3	10.3
Na	<0.03	<0.03	<0.03	19.80	72.10	63.20	41.00	7.80
As	0.005	0.003	0.006	0.002	0.003	0.007	0.006	0.003
B	<0.02	<0.02	<0.02	0.02	0.02	0.02	0.02	0.02
Be	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Cd	<0.03	<0.03	<0.003	<0.03	<0.03	<0.03	<0.03	
Cr	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Cu	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Hg	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Ni	<0.03	<0.03	<0.03	0.04	0.07	0.13	0.12	0.21
Pb	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Se	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Zn	<0.03	<0.03	<0.03	0.35	0.24	1.36	0.29	0.44

Note: All values are in mg/ℓ.

TABLE 12. CHEMICAL COMPOSITION OF GROUNDWATER OBTAINED FROM BORINGS AT LANDFILL B

	Up groundwater gradient			Under landfill			Down groundwater gradient	
Parameters	Boring 4	Boring 5	Boring 6	Boring 1	Boring 2	Boring 3	Boring 7	Boring 8
SO_4	<8	<8	<8	240	44	190	24	14
SO_3	<1	<1	<1	<1	12	10	<1	<1
Cl	<5	<5	<5	<5	12	10	<5	<5
NO_3-N	0.78	2.02	0.86	0.03	0.02	0.14	2.30	2.00
NO_2-N	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CN	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
TOC	8	20	14	32	22	148	10	21
Ca	160.0	75.0	95.0	210.0	170.0	190.0	180.0	190.0
Fe	0.2	0.2	0.2	20.0	0.2	0.2	0.2	0.2
Mg	78.0	30.0	39.0	111.0	6.8	130.0	117.0	120.0
Mn	0.567	0.016	0.030	11.300	0.983	2.000	2.35	8.97
Na	32.00	22.00	20.00	75.00	35.00	33.00	37.00	33.00
As	0.008	0.004	0.002	0.210	0.008	0.007	0.010	0.004
B	0.30	0.03	0.03	0.23	0.15	0.04	0.04	0.10
Be	0.0460	0.0005	0.0006	0.0540	0.0470	0.0510	0.0350	0.041
Cd	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Cr	0.05	0.05	<0.03	0.04	0.04	0.04	<0.03	<0.03
Cu	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Hg	0.0010	<0.0002	0.0007	<0.0002	0.0002	0.0003	0.0009	<0.0002
Ni	0.536	0.225	0.270	0.630	0.539	0.573	0.450	0.540
Pb	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Se	0.005	0.002	0.002	0.004	0.007	0.006	0.007	0.007
Zn	0.05	<0.03	<0.03	0.70	0.14	0.03	<0.03	0.10

Note: All values are in mg/ℓ

TABLE 13. CHEMICAL COMPOSITION OF GROUNDWATER OBTAINED FROM BORINGS AT LANDFILL C

	Up groundwater gradient				Under landfill			Down groundwater gradient	
Parameters	Boring 6	Boring 7	Boring 8	Boring 9	Boring 1	Boring 2	Boring 3	Boring 4	Boring 5
SO_4	<8	<8	<8	<8	9	24	8	8	8
SO_3	<1	<1	<1	<1	1	<1	2	<1	1
Cl	20	5	15	5	5	415	15	365	25
NO_3-N	0.03	0.02	0.68	0.11	0.04	0.03	0.02	<0.01	0.01
NO_2-N	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CN	<0.01	<0.01	<0.01	<0.01	0.01	0.01	<0.01	<0.01	<0.01
TOC	5	1	4	2	95	208	16	30	8
Ca	8.0	2.6	1.6	7.9	37.0	34.0	10.0	72.0	7.0
Fe	0.10	0.07	0.12	0.13	4.90	18.20	0.08	2.77	0.09
Mg	7.50	1.50	2.30	1.20	16.00	56.00	4.4	68.00	7.50
Mn	0.20	0.15	0.50	0.06	7.12	12.30	0.19	31.90	5.19
Na	12.00	5.90	6.00	2.90	7.50	220.00	6.70	71.00	5.90
As	0.002	0.002	0.002	0.002	0.002	0.003	0.002	0.002	0.002
B	0.04	<0.02	<0.02	0.06	0.12	1.45	1.06	1.04	<0.02
Be	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Cd	0.03	0.70	0.12	0.04	<0.03	<0.03	<0.03	0.05	0.09
Cr	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Cu	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Hg	0.0081	0.0039	0.0013	0.0018	0.0012	0.0014	0.0018	0.0012	0.0012
Ni	0.08	0.05	0.08	0.38	1.61	0.42	0.07	0.06	0.08
Pb	0.173	0.114	0.111	0.133	0.274	0.368	0.140	0.493	0.163
Se	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Zn	0.03	0.69	0.12	0.07	2.73	0.64	0.06	0.20	0.09

Note: All values are in mg/ℓ

TABLE 14. RESULTS OF ANALYSIS OF VARIANCE FOR GROUNDWATER CHEMISTRY

Parameter	Site A*	Site B*	Site C**
SO_4	S	S	S
SO_3	N	NS	NS
Cl	S	NS	NS
NO_3-N	NS	S	S
NO_2-N	NS	N	N
CN	NS	N	S
TOC	S	NS	S
Ca	S	NS	NS
Fe	S	NS	NS
Mg	S	NS	NS
Mn	S	NS	NS
Na	S	NS	NS
As	NS	NS	NS
B	S	NS	NS
Be	NS	NS	N
Cd	N	N	NS
Cr	NS	NS	N
Cu	N	N	N
Hg	N	NS	NS
Ni	S	NS	NS
Pb	N	N	NS
Se	N	NS	N
Zn	NS	NS	NS

S = Significant difference in means.
NS = No significant difference in means.
N = No present in measurable quantities in any sample.
* = Tested at 96.8% confidence level.
** = Tested at 95.4% confidence level.

samples (Wells A-4, A-5, A-8) contain very low levels of many elements. Therefore the contrast with the sub-landfill samples is strong and the number of statistically significant differences in averages is large. Site B and site C show higher background levels in the upgradient wells reflecting the more complex chemical composition of the materials in the area (clays at site B; weathered metamorphic rocks at site C). Therefore, the contrast between the upgradient groundwater samples and the sub-landfill samples is correspondingly weaker and the number of statistically significant differences in mean values for chemical parameters is lower.

The most consistent effect of leachate contamination observed in the groundwater is the increased sulfate noted in wells under the landfill as contrasted with upgradient wells. This increase was observed at all three landfills that were investigated. Increases in nitrate, or total organic carbon were observed in the sub-landfill groundwater samples in two out of the three sites. At site A, probably because of this site's low background levels, significant contrasts could also be found in chloride, calcium, iron, magnesium, sodium, boron, and nickel. Site C showed a significant contrast in cyanide levels under and upgradient from the landfill.

The results of this investigation agree with previous investigations in indicating that increased levels of sulfate, nitrate and organic carbon levels are related to pollution from landfill leachate (3,4,14). Cyanide measurements are not usually made on groundwater in municipal landfill areas, but as indicated by site C, cyanide may be a worthwhile measurement to make on leachate-contaminated water.

CHEMICAL ANALYSES OF DISTILLED WATER EXTRACTS

The goal of distilled water extraction was to determine the availability of the potential pollutants in the soil samples to water in contact with the soil. The availability of particular materials in sub-landfill soil to a distilled water extract may vary greatly from site to site. The content of this soil extract depends upon the:

a) original constituents in the soil and their solubilities,

b) way in which the original constituents have reacted with the weak organic acids in leachate and the solubilities of new products produced,

c) extent to which the water-soluble and leachate-soluble materials have been removed from the soil through solution,

d) solubilities of materials that are precipitated, filtered, or adsorbed from the leachate passing through the soil,

e) pH and redox conditions in the soil, especially as this effects the solubility of iron and manganese, the survival of nitrates and sulfates, and the production of sulfide, and

f) amount and character of the interstitial water present in the sample.

Comparison of Distilled Water Extracts from Beneath and Outside the Landfills

The tabulation of analyses of distilled water extracts of soil samples is given in Tables 15-20. Many of the analyses are close to or below the limits of detection indicating that in general very little material is available to contacting water in soils either under or away from the landfills. A statistical comparison was made between analyses of extracts obtained from samples immediately under the landfill and those collected at comparable depths below the surface (but above the water table) outside the landfill. A randomization procedure was used to test the significance of differences between means of the two sample sets. Using five samples, an 80% significance level can be obtained in a two-tailed test. The results of the randomization test are given in Table 21.

Only sulfate levels show a significant difference between means of samples obtained inside and outside the landfill at all three sites. There is, however, no consistent relationship in the behavior of sulfate between sites. At sites A and B the sulfate levels are slightly higher in the water leach from soil under the landfill. At site C the reverse is true. At all three sites, sulfate is moving from the landfill through the sub-refuse soil as shown by the increased sulfate levels in groundwater. At site C, sulfate from the leachate may be moving through the soil without being stopped or sulfate trapped in the soil may be reduced to sulfide through the activity of anaerobic bacteria decomposing organic materials in the leachate.

Chloride levels in soil extracts were significantly different inside and outside the landfills at sites B and C. At site C the sub-landfill soil extract was high in chloride compared to the samples outside the fill. At site B the reverse was true. Groundwater analyses indicated that chloride levels increased significantly only under landfill site C. The increased chloride in the soil sample at site C is to be expected from the increased supply of chloride from leachate. Chloride ion is not readily adsorbed to solid materials and does not readily precipitate. The increased chloride observed in the water extract from soil below the landfill at site C is probably due to chloride in solution in the water associated with the wet sample. At site B the decrease in chloride in extract from soil under the landfill is consistent with the low chloride levels seen in the groundwater.

Nitrate levels were significantly different inside and outside of the landfill only at site C. Very low nitrate levels were observed inside the landfill and higher levels outside. The nitrogen present in soil under the landfill might be converted from nitrate to ammonium ion through bacterial activity associated with the leachate; reducing nitrate below levels observed in similar surrounding soils. Published analyses indicate much of the nitrogen in leachate is present as ammonium ion (1), not as nitrate, indicating nitrate reduction can occur, and that nitrogen added to the sub-landfill soil probably is in the form of ammonium ion.

Cyanide levels varied significantly only at site B. The analyses are mostly at or very near the limits of detection for this constituent and so

TABLE 15. ANALYSES OF DISTILLED WATER EXTRACTS OF SOIL SAMPLES FROM EXPERIMENTAL BORINGS AT SITE A

Boring and sample	2C4	2C5	2C6	3C1	3C2	3C3	3C4	3C5	3C6
Elevation (m)	243.00	237.11	232.08	250.53	249.53	247.60	240.27	235.72	230.73
Depth below mw/soil interface (m)	7.99	13.87	18.90	0.00	1.01	2.93	10.26	14.81	19.80
Ht. above water table (m)	11.99	6.10	1.07	19.31	18.31	16.38	9.05	4.50	-0.49
Conc. (mg/ℓ)									
SO_4	9	8	9	9	9	9	9	9	9
SO_3	<1	<1	<1	<1	<1	<1	<1	<1	<1
Cℓ	<5	<5	<5	<5	<5	<5	<5	<5	<5
NO_3-N	0.01	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
NO_2-N	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CN	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
TOC	6	6	7	7	4	5	2	7	5
Ca	0.18	0.15	2.24	0.54	0.77	0.55	2.23	1.53	0.44
Fe	ND	ND	ND	ND	ND	ND	ND	ND	ND
Mg	0.10	0.12	0.80	0.22	0.14	0.23	1.31	0.92	0.13
Mn	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Na	0.42	0.94	0.70	2.29	6.47	3.58	0.19	2.97	1.90
As	0.002	0.002	0.002	0.006	0.010	0.004	0.002	0.004	0.002
B	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Be	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Cd	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Cr	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Cu	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Hg	ND	ND	ND	ND	ND	ND	ND	ND	ND
Ni	<0.03	<0.03	<0.03	0.07	0.04	<0.03	<0.03	<0.03	<0.03
Pb	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Se	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Zn	0.21	1.39	0.38	0.35	0.22	1.12	0.06	0.21	1.14

ND = Not determined

TABLE 15. (continued)

Boring and sample	1C1	1C2	1C3	1C4	1C5	1C6	1C7	2C1	2C2	2C3
Elevation (m)	250.57	249.77	247.58	242.08	234.81	230.83	230.83	250.98	250.14	247.99
Depth below mw/soil interface (m)	0.00	0.82	3.02	8.52	15.78	19.77	19.77	0.00	0.84	2.99
Ht. above water table (m)	18.06	17.24	15.05	9.55	2.28	-1.70	-1.70	19.97	19.13	16.98
Conc. (mg/ℓ)										
SO_4	9	10	9	10	9	42	9	9	9	9
SO_3	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Cl	<5	<5	<5	5	5	5	<5	<5	<5	<5
NO_3-N	0.30	0.01	<0.01	0.03	<0.01	0.13	<0.01	0.38	0.06	<0.01
NO_2-N	<0.01	<0.01	<0.01	<0.01	<0.01	0.06	<0.01	0.09	<0.01	<0.01
CN	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
TOC	9	11	8	8	6	8	5	10	9	10
Ca	0.31	1.40	0.35	0.70	0.59	3.03	1.22	0.41	3.58	0.95
Fe	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Mg	0.48	0.97	0.33	0.67	0.18	1.69	0.29	0.30	0.68	0.20
Mn	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	0.07	0.06	<0.03
Na	2.94	1.40	1.10	2.62	0.93	0.53	1.78	3.20	1.82	1.94
As	0.006	0.002	0.001	0.002	0.001	0.008	0.001	0.002	0.002	0.001
B	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Be	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.02	<0.02	<0.02	<0.02
Cd	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	0.03	<0.03	<0.03	<0.03
Cr	<0.03	<0.03	<0.03	0.03	<0.03	0.05	<0.03	0.28	<0.03	0.03
Cu	0.03	<0.02	<0.02	<0.02	<0.02	0.04	<0.02	0.17	<0.02	0.02
Hg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Ni	0.09	<0.03	<0.03	0.08	<0.03	0.05	0.07	2.62	<0.03	<0.03
Pb	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Se	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Zn	0.78	1.10	0.11	0.38	0.13	0.82	0.29	4.65	0.10	0.46

(continued)

TABLE 16. ANALYSES OF DISTILLED WATER EXTRACTS OF SOIL SAMPLES FROM CONTROL BORINGS AT SITE A

Boring and sample	6C1	6C2	6C3	6C4	6C5	6C6	7C1	7C2	7C3	7C4	7C5	7C6
Elevation (m)	251.09	250.20	248.08	242.05	236.86	230.84	250.49	250.15	247.99	242.23	236.37	233.32
Ht. above water table (m)	19.99	19.10	16.98	10.95	5.76	-0.26	14.97	14.63	12.47	6.71	-0.85	-2.20
Conc. (mg/ℓ)												
SO_4	9	10	8	8	8	8	8	8	8	9	10	10
SO_3	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Cℓ	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5
NO_3-N	0.02	0.01	0.01	0.16	0.06	<0.01	0.05	0.04	0.27	0.02	0.05	0.20
NO_2-N	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CN	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
TOC	3	<1	3	2	2	<1	<1	<1	<1	5	5	3
Ca	0.37	0.30	1.26	0.46	0.30	0.18	0.51	0.72	0.98	0.87	1.24	2.02
Fe	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Mg	0.16	0.23	0.51	0.28	0.21	0.16	0.14	0.35	0.33	0.35	0.54	0.91
Mn	<0.03	<0.03	<0.03	<0.03	0.04	<0.03	<0.03	<0.03	0.03	0.06	0.03	0.04
Na	0.27	0.21	0.30	0.32	0.39	0.49	0.73	0.39	0.70	0.61	0.37	0.33
As	0.004	0.002	0.001	0.001	0.001	0.001	0.002	0.002	0.002	0.002	0.002	0.002
B	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Be	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Cd	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Cr	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Cu	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Hg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Ni	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Pb	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Se	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Zn	0.91	0.14	0.25	<0.03	0.68	0.27	0.35	0.09	0.22	<0.03	0.20	0.39

ND = Not determined
NOTE: All borings are positioned downdip on the groundwater gradient.

TABLE 17. ANALYSES OF DISTILLED WATER EXTRACTS OF SOIL SAMPLES FROM EXPERIMENTAL BORINGS AT SITE B

Boring and sample	1C1	1C2	2C1	2C2	2C3	3C1	3C2	3C3
Elevation (m)	55.93	54.06	56.77	55.85	53.72	56.74	55.74	53.50
Depth below soil/mw interface (m)	0.00	1.87	0.00	0.92	3.05	0.00	1.00	3.24
Ht. above water table (m)	1.57	-0.30	5.83	4.91	2.78	3.51	2.51	0.27
Conc. (mg/ℓ)								
SO_4	<8	25	<8	<8	<8	9	<8	13
SO_3	<1	<1	<1	<1	<1	<1	<1	<1
Cl	5	8	<5	<5	8	<5	<5	<5
NO_3-N	0.04	0.07	0.02	0.05	0.05	0.27	0.17	<0.01
NO_2-N	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CN^-	0.01	0.01	0.01	0.01	<0.01	0.02	0.01	<0.01
TOC	14	10	16	14	6	27	12	4
Ca	20.00	13.00	21.00	18.00	19.00	6.50	15.00	21.00
Fe	0.50	0.48	0.25	0.20	0.05	0.40	0.10	0.11
Mg	11.70	5.60	8.50	8.00	6.60	4.10	12.00	9.90
Mn	0.30	0.99	0.04	0.11	<0.03	<0.03	0.26	<0.03
Na	21.00	6.70	30.00	13.00	3.00	66.00	9.40	4.10
As	ND	ND	ND	ND	ND	ND	ND	ND
B	0.05	0.06	0.15	0.09	<0.02	<0.02	<0.02	<0.02
Be	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Cd	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Cr	0.05	0.05	0.07	0.05	<0.03	<0.03	<0.03	<0.03
Cu	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Hg	ND	ND	ND	ND	ND	ND	ND	ND
Ni	0.10	0.08	0.13	0.11	0.05	0.06	0.05	0.07
Pb	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Se	ND	ND	ND	ND	ND	ND	ND	ND
Zn	<0.03	<0.05	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10

ND = Not determined.

TABLE 18. ANALYSES OF DISTILLED WATER EXTRACTS OF SOIL SAMPLES FROM CONTROL BORINGS AT SITE B

Boring and sample	5C1	5C2	5C3	6C1	6C2	6C3	7C3
Elevation (m)	55.28	54.38	52.44	54.26	53.35	51.22	42.00
Ht. above water table (m)	1.93	1.03	-0.91	4.11	3.20	1.07	0.10
Position in groundwater gradient	updip	updip	updip	updip	updip	updip	downdip
Conc. (mg/ℓ)							
SO_4	<8	<8	<8	<8	<8	<8	<8
SO_3	<1	<1	<1	<1	<1	<1	<1
Cl	8	5	12	8	13	31	<5
NO_3-N	1.56	0.25	0.09	0.24	2.11	0.05	0.08
NO_2-N	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CN	0.01	0.01	<0.01	<0.01	0.01	0.01	0.01
TOC	3	10	6	4	6	20	10
Ca	36.00	33.00	27.00	27.00	34.00	40.00	35.00
Fe	0.14	0.10	0.10	0.10	0.20	0.10	0.14
Mg	10.50	11.50	9.20	10.20	12.00	14.00	17.00
Mn	<0.03	<0.03	<0.03	<0.03	0.04	<0.03	0.14
Na	3.30	3.50	3.60	4.30	4.30	4.30	23.00
As	ND	ND	ND	ND	ND	ND	ND
B	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.06
Be	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Cd	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Cr	<0.03	<0.03	<0.03	<0.03	0.04	<0.03	<0.03
Cu	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Hg	ND	ND	ND	ND	ND	ND	ND
Ni	0.12	0.11	0.10	0.10	0.12	0.14	0.15
Pb	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	1.00
Se	ND	ND	ND	ND	ND	ND	ND
Zn	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	0.06

ND = Not determined.

TABLE 19. ANALYSES OF DISTILLED WATER EXTRACTS OF SOIL SAMPLES FROM EXPERIMENTAL BORINGS AT SITE C

Boring and sample	1C1	1C2	1C3	2C1	2C2	2C3	3C1	3C2	3C3
Elevation (m)	131.41	130.48	128.34	127.46	126.55	124.41	125.50	124.57	123.20
Depth below mw/soil interface (m)	0.00	0.93	3.07	0.00	0.91	3.05	0.00	0.93	2.30
Ht. above water table (m)	4.40	3.47	1.33	0.20	-0.71	-2.85	2.48	1.55	0.18
Conc. (mg/ℓ)									
SO_4	9	<8	<8	8	<8	<8	<8	<8	<8
SO_3	<1	<1	<1	<1	<1	<1	<1	<1	<1
Cl	5	5	5	10	5	10	10	5	10
NO_3-N	0.03	0.03	0.02	0.01	0.06	0.02	0.02	0.03	0.02
NO_2-N	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CN	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
TOC	21	18	4	8	1	8	8	4	2
Ca	0.60	2.10	3.00	1.60	1.30	1.20	0.70	0.80	0.80
Fe	0.09	0.15	0.09	0.07	0.06	0.07	0.05	<0.05	<0.05
Mg	1.60	1.30	1.90	1.30	1.00	0.90	1.80	0.45	0.70
Mn	0.60	0.27	0.05	0.05	0.06	0.61	0.60	0.74	<0.03
Na	2.20	2.00	2.40	3.90	2.80	9.20	4.90	5.50	2.10
As	ND	ND	ND	ND	ND	ND	ND	ND	ND
B	<0.02	<0.02	<0.02	0.02	<0.02	<0.02	0.02	0.02	<0.02
Be	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Cd	0.04	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Cr	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Cu	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Hg	ND	ND	ND	ND	ND	ND	ND	ND	ND
Ni	0.06	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Pb	ND	ND	ND	ND	ND	ND	ND	ND	ND
Se	ND	ND	ND	ND	ND	ND	ND	ND	ND
Zn	0.06	0.20	0.27	0.05	0.09	0.06	0.04	0.03	0.05

ND = Not determined.

TABLE 20. ANALYSES OF DISTILLED WATER EXTRACTS OF SOIL SAMPLES FROM CONTROL BORINGS AT SITE C

Boring and sample	6C1	6C2	6C3	6C4	6C5	7C4	8C3	9C1	9C2	9C3	9C4	9C5	4C6	5C4
Elevation (m)	132.46	131.54	129.41	127.88	126.06	121.80	130.14	143.47	142.57	140.44	136.17	131.91	124.74	126.92
Ht. above water table (m)	5.42	4.50	2.37	0.84	−0.98	0.09	−0.36	11.47	10.57	8.44	4.17	−0.09	−0.66	−0.12
Position in groundwater gradient	Updip	Updip	Updip	Updip	Updip	Updip	Updip	Updip	Updip	Updip	Updip	Updip	Downdip	Downdip
Conc. (mg/ℓ)														
SO_4	12	<8	11	<8	<8	<8	<8	20	10	16	16	<8	<8	<8
SO_3	<1	<1	<1	<1	<1	<1	<1	2	<1	2	<1	<1	<1	<1
Cl	5	5	10	5	20	20	30	5	15	5	5	15	75	30
NO_3-N	1.34	1.69	1.75	3.06	1.54	0.87	1.91	1.91	1.82	1.57	0.07	1.98	<0.01	1.27
NO_2-N	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CN	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
TOC	14	13	14	6	2	1	5	6	6	1	6	6	4	6
Ca	6.90	1.10	1.40	2.10	2.60	2.20	2.70	10.00	23.00	7.40	2.30	2.70	14.00	3.80
Fe	0.89	0.34	5.26	0.10	0.10	0.05	0.08	7.95	0.08	0.06	0.05	<0.05	0.12	0.09
Mg	1.50	1.20	1.50	1.00	1.00	1.80	3.90	2.20	2.50	2.90	0.50	1.00	8.00	1.80
Mn	1.76	<0.03	<0.03	<0.03	<0.03	<0.03	0.14	0.03	<0.03	0.05	<0.03	<0.03	3.31	0.26
Na	2.60	4.60	8.10	6.60	3.20	3.60	2.30	2.80	2.20	2.10	1.90	2.10	6.70	2.10
As	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
B	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.10	0.04	0.04	0.04	<0.02	0.02	0.02
Be	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Cd	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Cr	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Cu	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Hg	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Ni	0.04	<0.03	<0.03	<0.03	0.03	<0.03	0.05	0.05	0.10	0.05	<0.03	<0.03	0.10	0.03
Pb	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	1.40	0.10	0.20	0.10	<0.10	1.59	<0.10	<0.10
Se	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Zn	0.13	0.07	0.07	0.08	0.27	0.11	0.18	0.07	0.34	0.23	0.15	0.08	0.13	0.15

ND = Not determined.

TABLE 21. RESULTS OF RANDOMIZATION TEST ON DISTILLED WATER EXTRACTS OF SOIL SAMPLES DIRECTLY UNDER THE LANDFILLS AND AT COMPARABLE DEPTHS OUTSIDE THE LANDFILLS

Parameters	Site A	Site B	Site C
SO_4	S	S	S
SO_3	N	N	N
Cl	N	S	S
NO_3-N	NS	NS	S
NO_2-N	N	N	N
CN	N	S	N
TOC	S	S	NS
Ca	NS	S	S
Fe	ND	S	S
Mg	S	NS	NS
Mn	N	S	NS
Na	S	S	NS
As	NS	ND	ND
B	N	S	NS
Be	N	N	N
Cd	N	N	N
Cr	S	S	N
Cu	S	N	N
Hg	ND	ND	ND
Ni	S	NS	NS
Pb	N	N	ND
Se	N	ND	ND
Zn	NS	N	S

N = Too few samples above detection limit.

ND = Not determined.

NS = Not significant at 80% level.

S = Significant at 80% level.

cannot be regarded as firm evidence of increased cyanide levels under the landfill at site B.

Total organic carbon (TOC) analyses show a pronounced difference between sub-landfill and control samples at both sites A and B. Samples below the landfills were consistently higher in TOC than those outside the landfill. All of the analyses under the landfills were well above the detection limits and at least double the analyses of control samples from outside the landfill. The groundwater analyses also indicated higher TOC levels in some borings beneath each landfill. These increased organic carbon levels can be attributed to material derived from the refuse.

Calcium levels in extracts from soils below the landfills at sites B and C are significantly lower than those extracts obtained from similar samples outside the landfills. However, calcium levels in the groundwater showed an increase under each landfill. These analyses indicate that the calcium availability is significantly decreased at sites B and C due to removal of soluble calcium compounds by landfill leachate or the production of insoluble calcium compounds by reaction with leachate.

Total iron levels were significantly different in soil extracts obtained below and outside the landfills at sites B and C. At site B the soil under the landfill showed more water-extractable iron than the soil samples outside the landfill. Site C showed the reverse trend. The availability of iron to contacting water is related to the redox conditions present, the complexing properties of organic materials in the soil, and the presence of anions such as sulfide, etc. that can produce insoluble iron compounds. The lack of extractable iron under the landfill at site C is consistent with the evidence of sulfate reduction discussed above.

Magnesium in water extracts showed a significant difference only at site A. Magnesium availability was only slightly higher in soil under the landfill than in soil outside the landfill.

Manganese levels were very slightly higher in soil extracts obtained under the landfill at site B as compared to samples outside the landfill. However, the observed levels are close to the analytical limits of detection.

Sodium in the water extracts showed a significant difference between control and experimental samples at sites A and B. At both sites, the available sodium increased under the landfill as compared to samples outside the landfill area. Sodium is a common constitutent in municipal landfill leachate; it does not really precipitate and is only weakly adsorbed.

Boron and the trace metals chromium, copper and nickel show higher levels in water extracts from soils under the landfills as compared to soils outside the landfill. These elements may be either freed from the soil by organic acids from the leachate or introduced in a soluble form in the leachate.

Zinc levels obtained from water extracts of soil samples at site C showed significant differences between samples collected under the landfill and those collected outside the landfill. The extracts from outside the landfill were slightly higher suggesting zinc was less available in the area affected by landfill leachate. Zinc is the only trace metal that could be shown to be extracted in greater concentrations outside the landfill than below the landfill. The immobilization of zinc may be related to sulfide production at site C.

The major factors that control availability of contaminants to a distilled water extract in sub-landfill soils studied are the supply of materials moving from the refuse to the soil, and the decrease in soluble constituents that occurs in the soil either due to leaching or production of insoluble compounds by reaction with leachate. Sulfate, if it is not reduced to sulfide, is more available under the landfill due to influx from the refuse. Chloride, total organic carbon, sodium and magnesium and all of the trace metals with the exception of zinc can appear in greater quantities in water extracts probably due to greater supply of these materials in a soluble form in the incoming leachate. Calcium in two cases showed a decrease of availability in sub-refuse soil possibly due to prior removal by solution or the formation of insoluble calcium compounds (possibly calcium salts of fatty acids). Iron and zinc at one site (site C) showed decreased availability in water extracts that can probably be attributed to formation of sulfides of these metals.

Vertical Variation of Constituents in the Distilled Water Extracts of Soil Samples

For those elements at each site that did show a significant difference in means between control (outside landfill) samples and experimental (inside landfill) samples, a test was made for a significant relationship between the available concentration of a particular constituent and sample elevation (or sample depth). The model suggests that those materials derived from the refuse would show a positive correlation with elevation in the experimental borings (below the landfill). Soil constituents that are being dissolved by the landfill leachate and moved down out of the soil and into the groundwater should, in the model situation, show a significant negative correlation with sample elevation. Outside the landfill the distribution of available soil constituents depends on weathering processes and the concentration and solubility of the particular material and could therefore have a significant positive or negative correlation with elevation, or no significant correlation at all.

The Spearman rank correlation was used to judge the strength of association because this technique could be used with small sample numbers where the statistical distribution is not known. In several cases, the small number of samples having detectable quantities of a particular constituent made it impossible to judge the significance of the correlation coefficients obtained. The results of the statistical tests are given in Tables 22-24. Plots of concentration versus sample elevation for all constituents that showed statistically significant relations with elevation in experimental borings are presented in Figures 7-18. Plots of significant relationships in control holes are included for contrast. The only significant correlation with sample elevation in borings through the landfill at site A (Borings 1, 2, and 3) involves total organic carbon. The correlation is positive as would be expected for a constituent derived from the refuse in the landfill. No significant correlation between sample elevation and total organic carbon could be observed in the control holes.

TABLE 22. CORRELATION OF CHEMICAL ANALYSES OF DISTILLED WATER EXTRACTS OF SOIL SAMPLES WITH SAMPLE ELEVATION AT SITE A

Boring No.	Experimental			Control	
	1	2	3	6	7
SO_4	NS	NS	NS	SP	SN
TOC	SP	NS	NS	NS	NS
Mg	NS	NS	NS	NS	SN
Na	NS	NS	NS	SN	SP
Cr	*	*	*	*	*
Cu	*	*	*	*	*
Ni	NS	*	NS	*	*

SP = Significant positive correlation at 95% level.

SN = Significant negative correlation at 95% level.

NS = Not significant.

* = Too few samples above detection limit.

TABLE 23. CORRELATION OF CHEMICAL ANALYSES OF DISTILLED WATER EXTRACTS OF SOIL SAMPLES WITH SAMPLE ELEVATION AT SITE B

Boring	Experimental			Control	
No.	1	2	3	5	6
SO_4	--**	*	NS	*	*
Cl	--	*	*	NS	SN
CN	--	*	SP	*	*
TOC	--	SP	SP	NS	SN
Ca	--	NS	SN	SP	SN
Fe	--	SP	NS	NS	NS
Mn	--	NS	*	*	*
Na	--	SP	SP	SN	NS
B	--	SP	*	*	*
Cr	--	SP	*	*	*
Zn	--	SP	*	*	*

SP = Significant positive correlation at 95% level.

SN = Significant negative correlation at 95% level.

NS = Not significant correlation.

* = Too few samples above detection limits.

** = Too few samples for significant test for this boring.

TABLE 24. CORRELATION OF CHEMICAL ANALYSES OF DISTILLED WATER EXTRACTS OF SOIL SAMPLES WITH SAMPLE ELEVATION AT SITE C.

Boring	Experimental			Control	
No.	1	2	3	6	9
SO_4	*	*	*	SP	NS
Cl	NS	NS	NS	NS	NS
NO_3	NS	NS	NS	NS	NS
Ca	SN	SP	NS	NS	NS
Fe	NS	NS	*	NS	SP
Zn	SN	NS	NS	NS	NS

SP = Significant positive correlation at 95% level.

SN = Significant negative correlation at 95% level.

NS = Not significant.

* = Too few samples above detection limit.

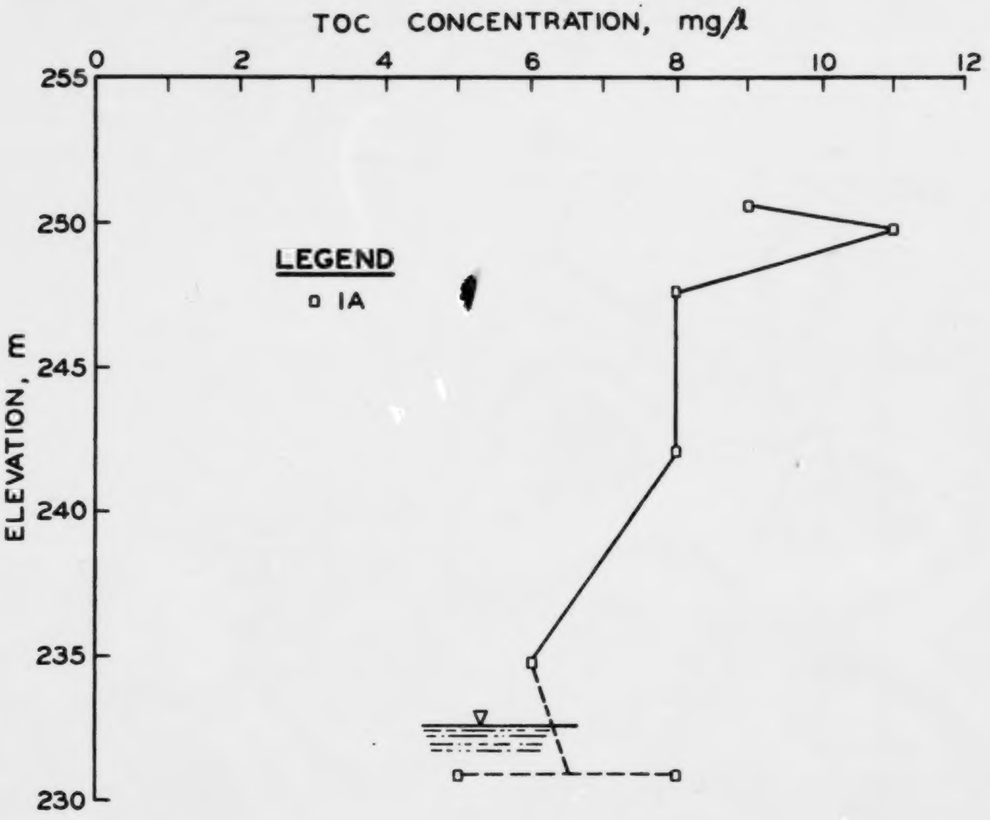


Figure 7. Variation of total organic carbon (TOC) concentration in distilled water extracts of soil/sediment samples with elevation in boring 1 at site A. Inverted triangle symbol indicates water table.

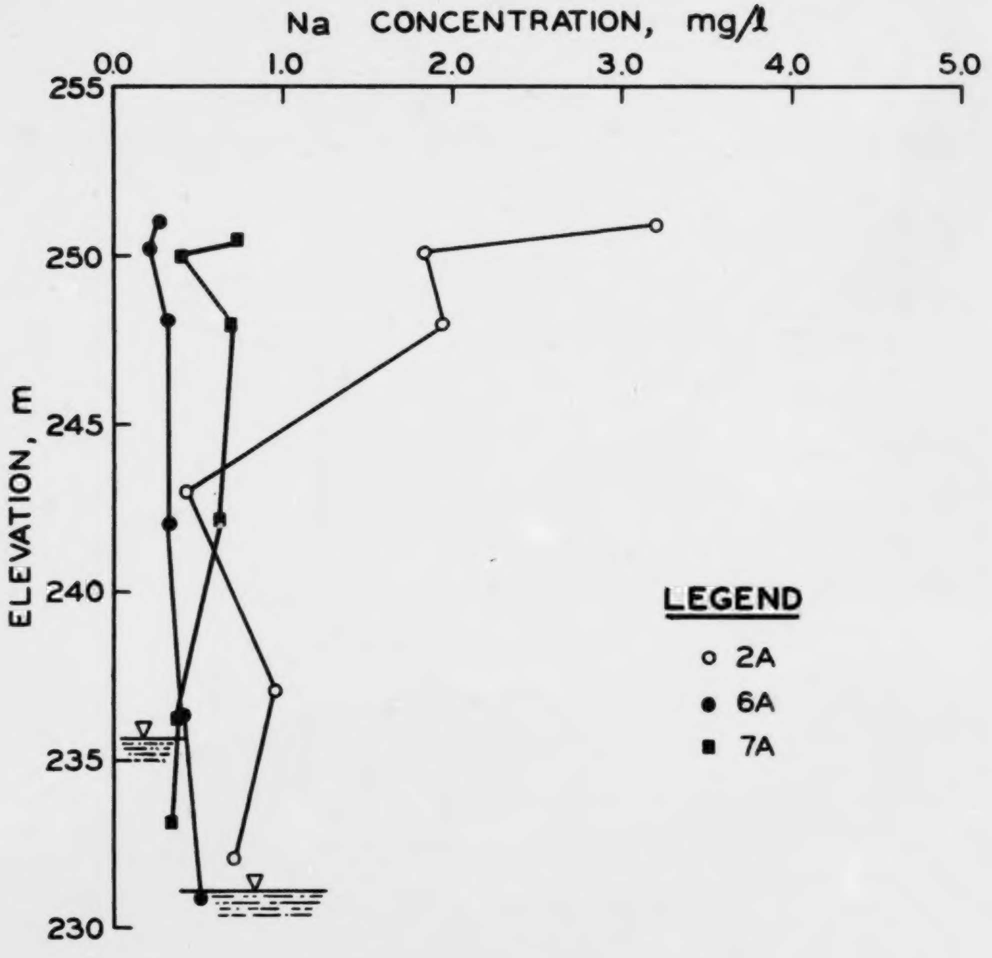


Figure 8. Variation of sodium concentration in distilled water extracts of soil/sediment samples with elevation in borings 2, 6, and 7 at site A. Inverted triangle symbols indicates water table in each boring.

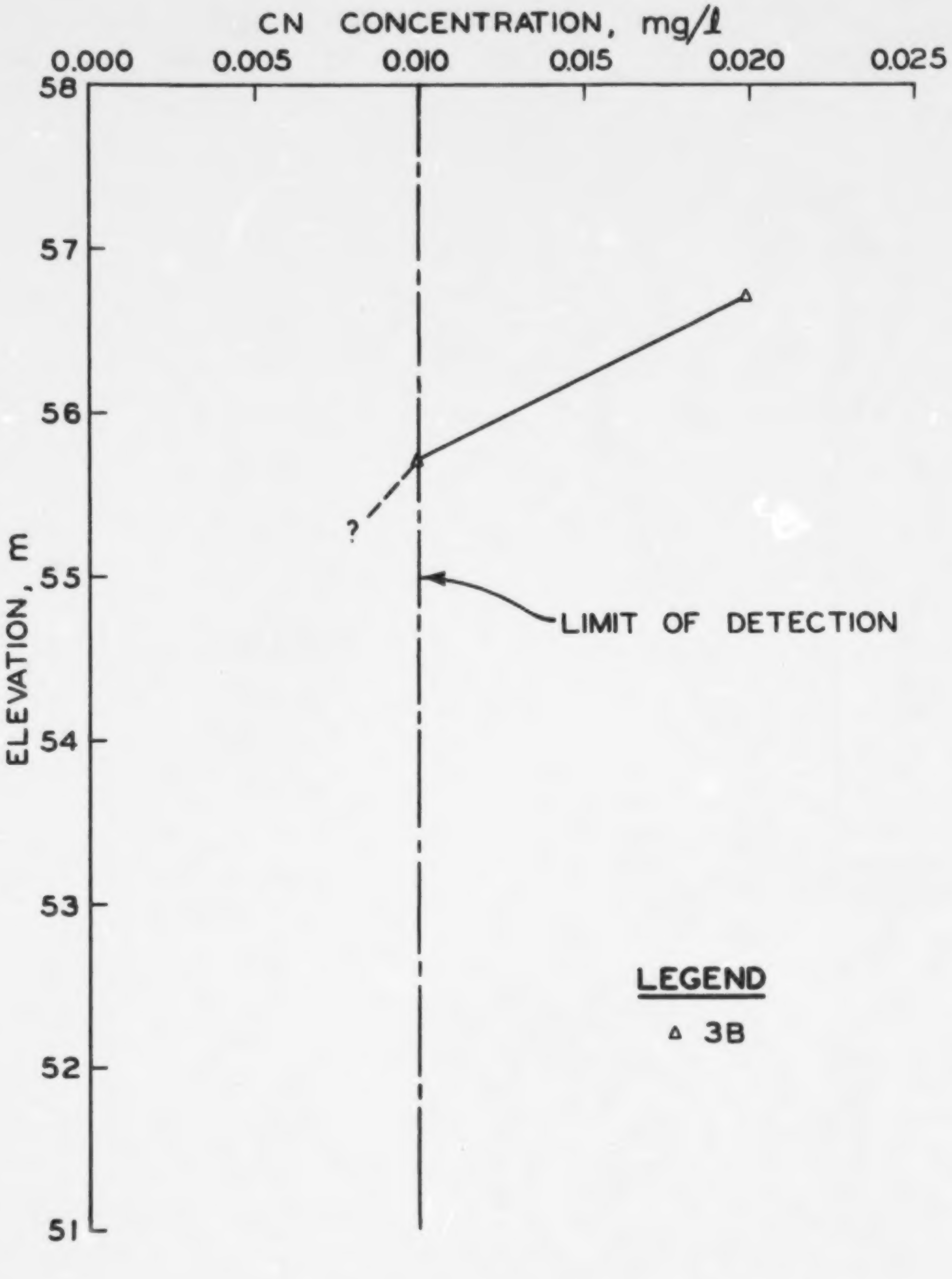


Figure 9. Variation of cyanide concentration in distilled water extracts of soil/sediment samples with elevation in boring 3 at site B.

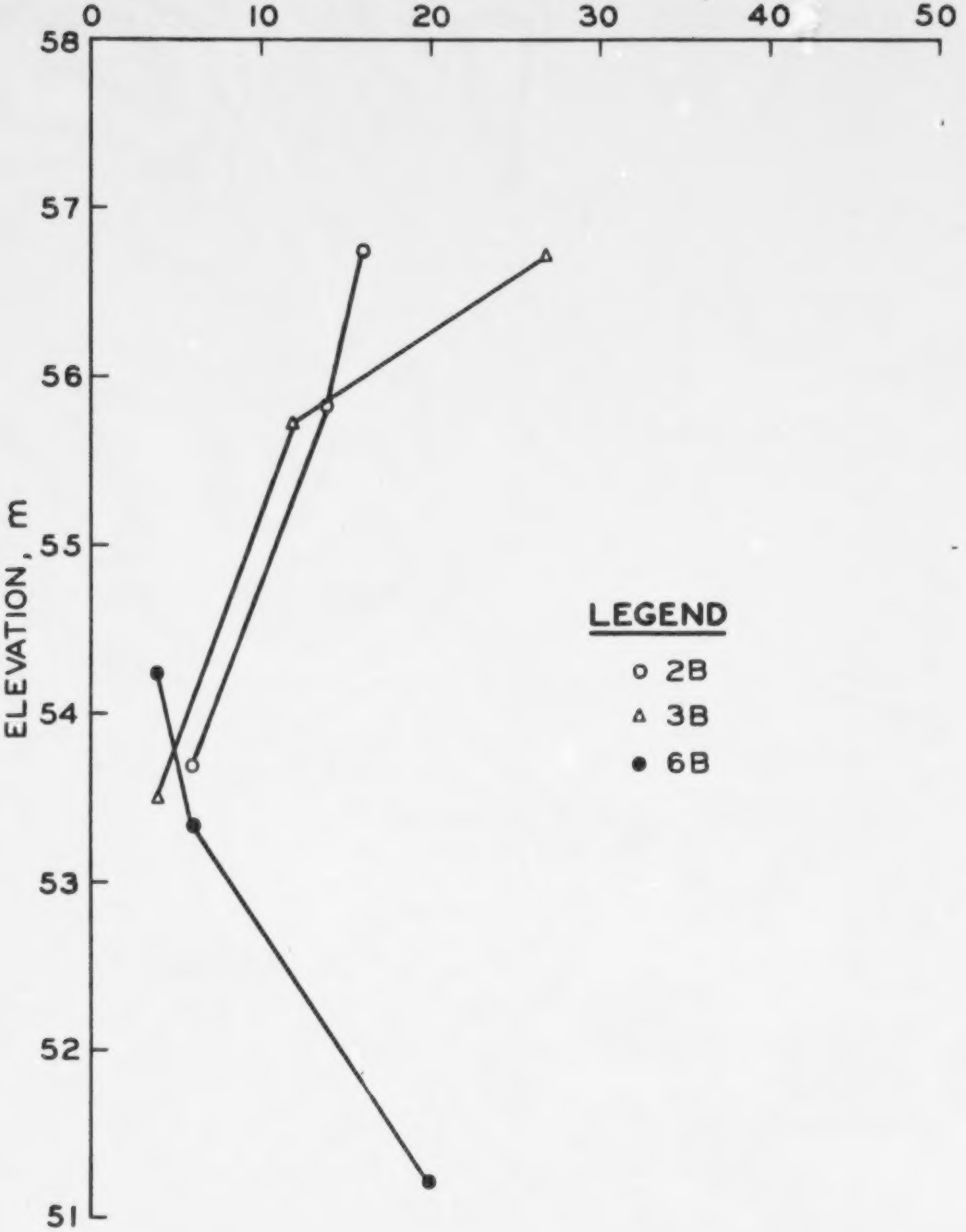


Figure 10. Variation in total organic carbon (TOC) concentration in distilled water extracts of soil/sediment samples with elevation in borings 2, 3, and 6 at site B.

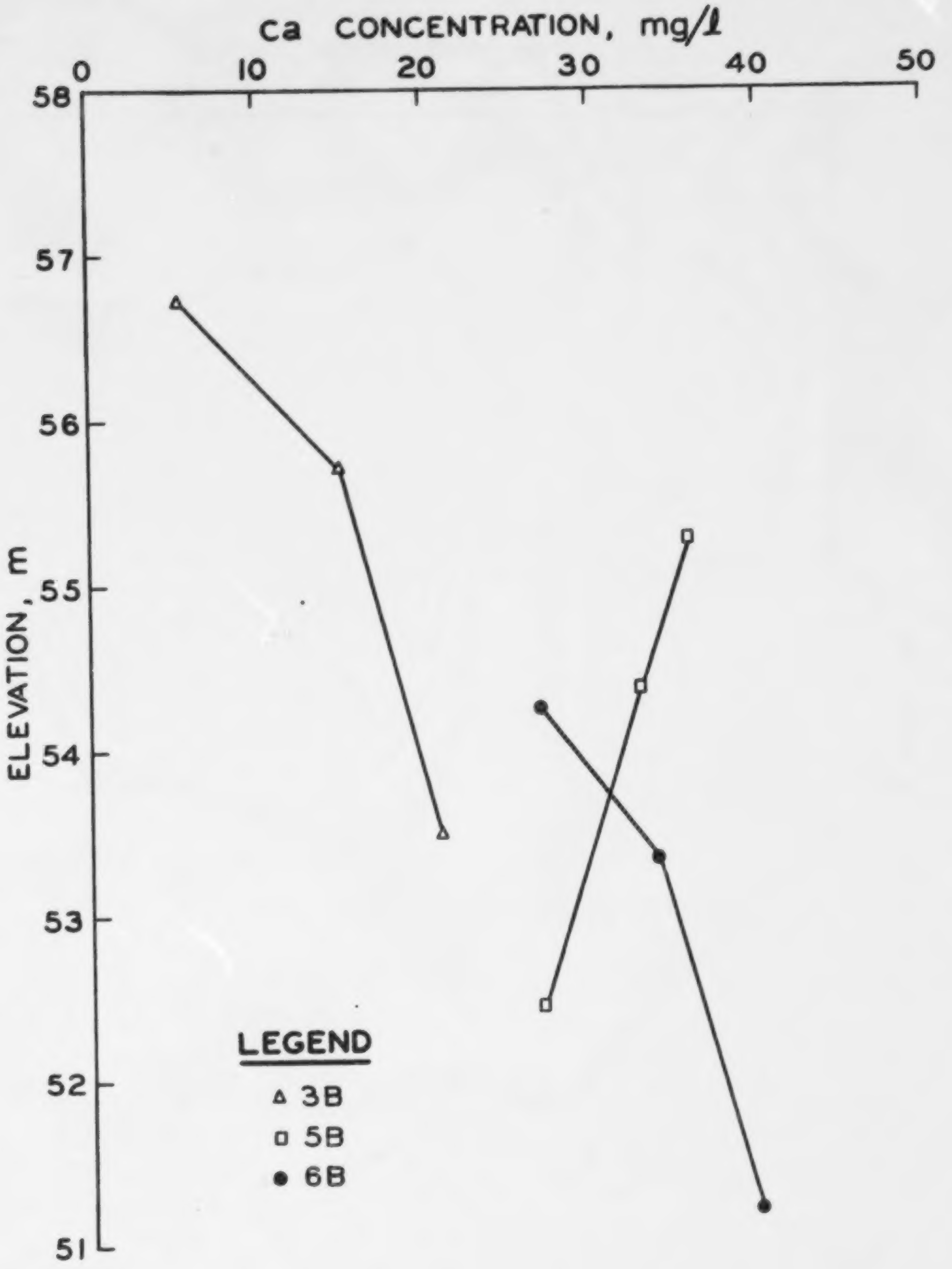


Figure 11. Variation of calcium concentration in distilled water extracts of soil/sediment samples with elevation in borings 3, 5, and 6 at site B.

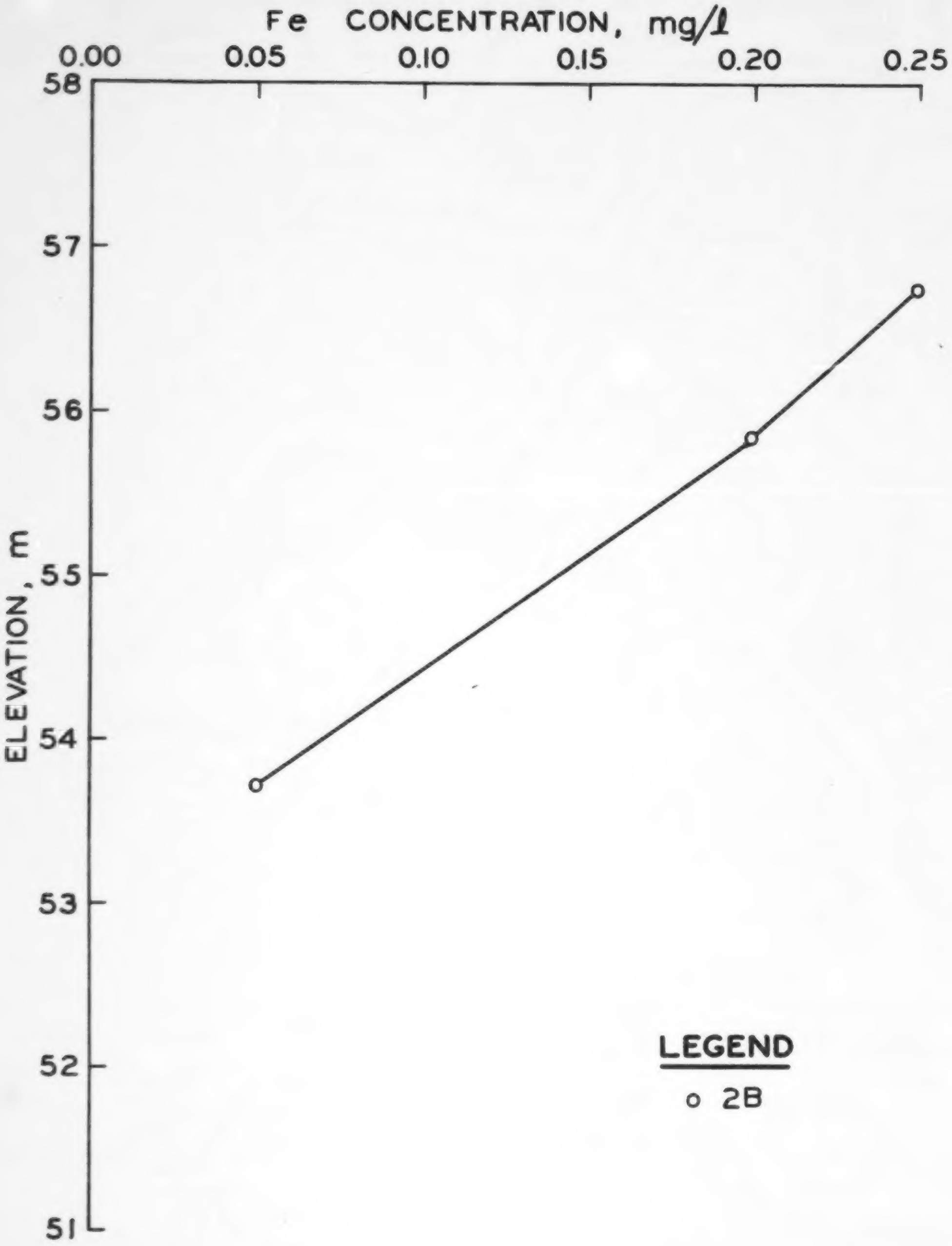


Figure 12. Variation of iron concentration in distilled water extracts of soil/sediment samples with elevation in boring 2 at site B.

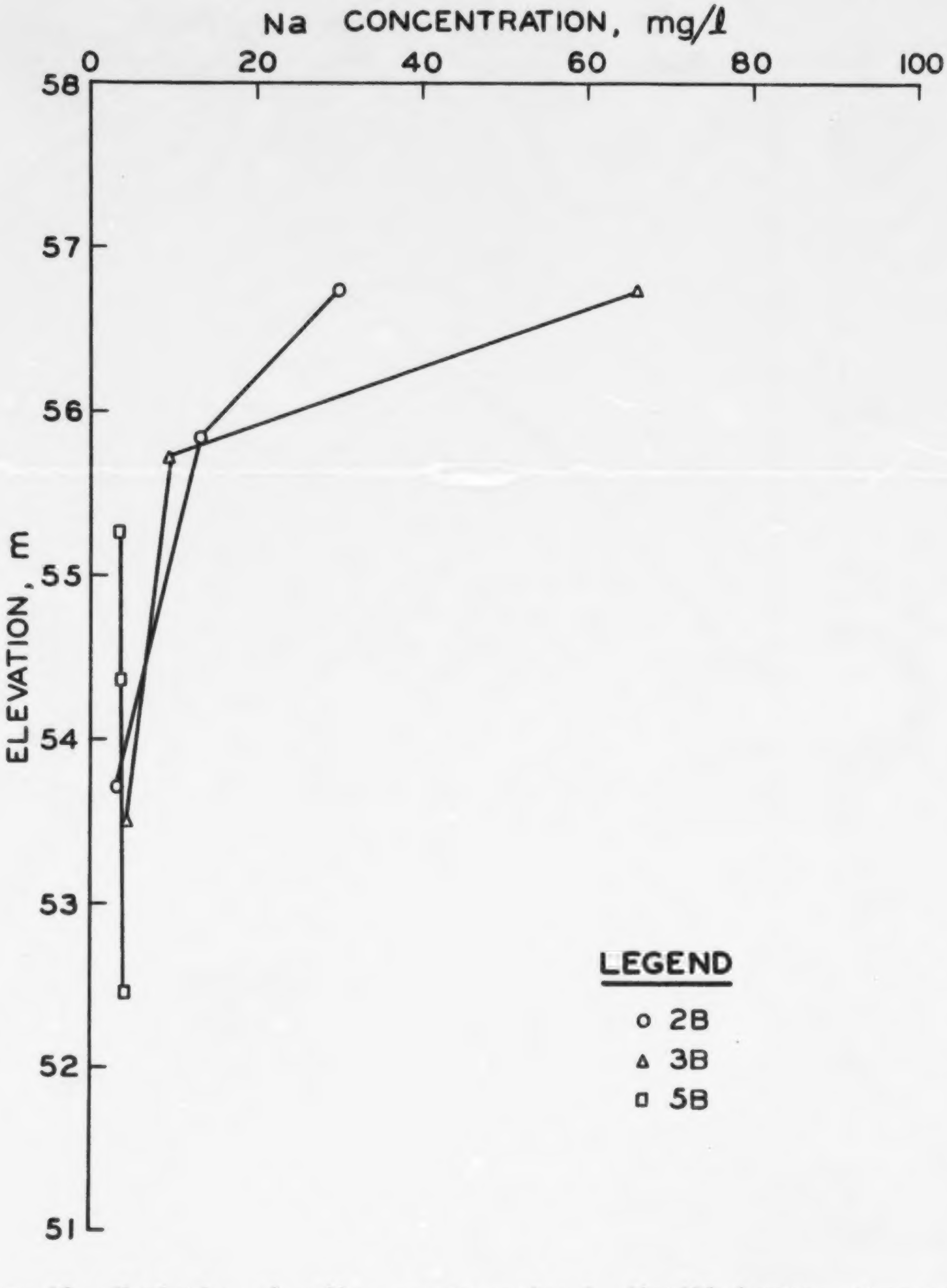


Figure 13. Variation of sodium concentration in distilled water extracts of soil/sediment samples with elevation in borings 2, 3, and 5 at site B.

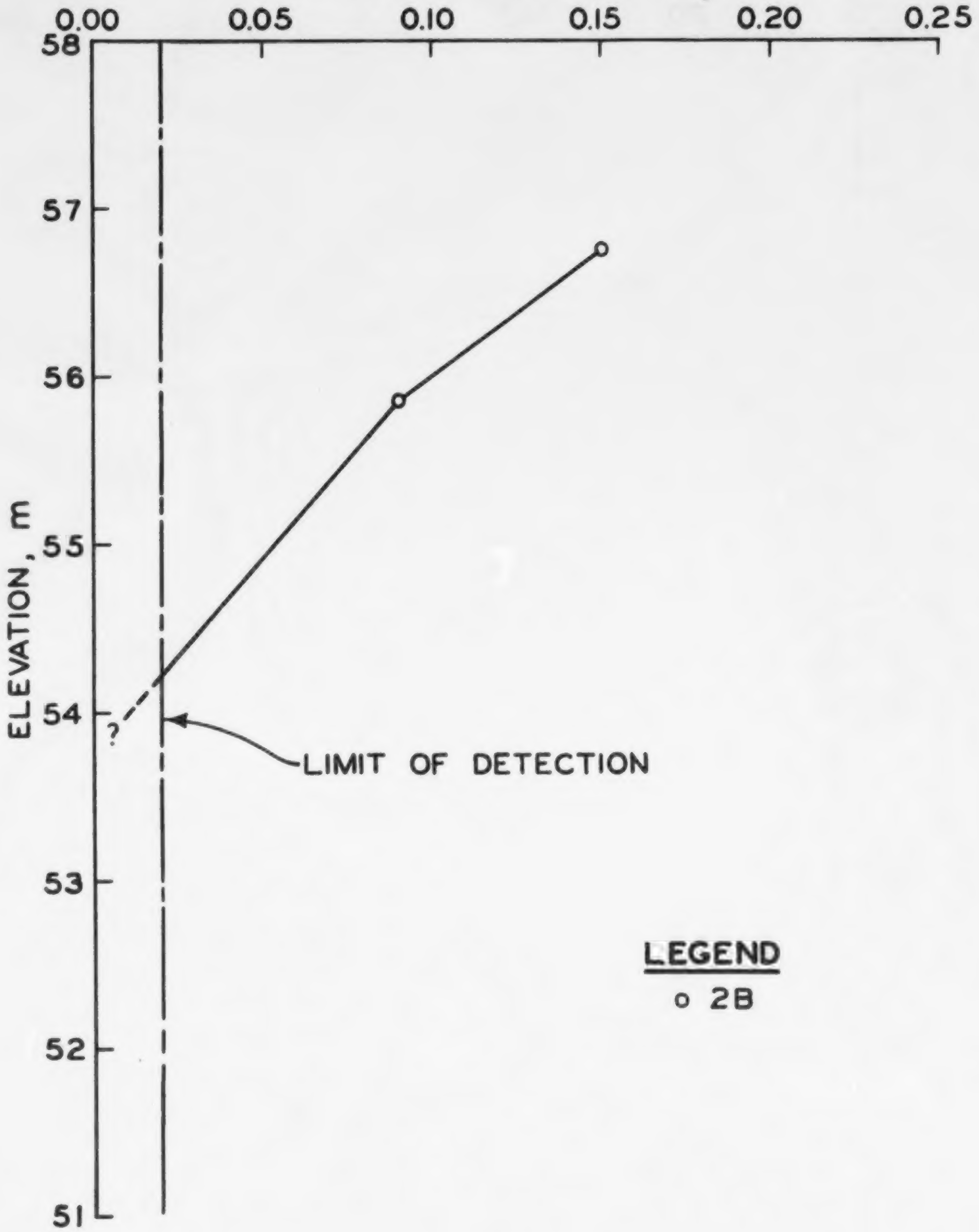


Figure 14. Variation of boron concentration in distilled water extracts of soil/sediment samples with elevation in boring 2 at site B.

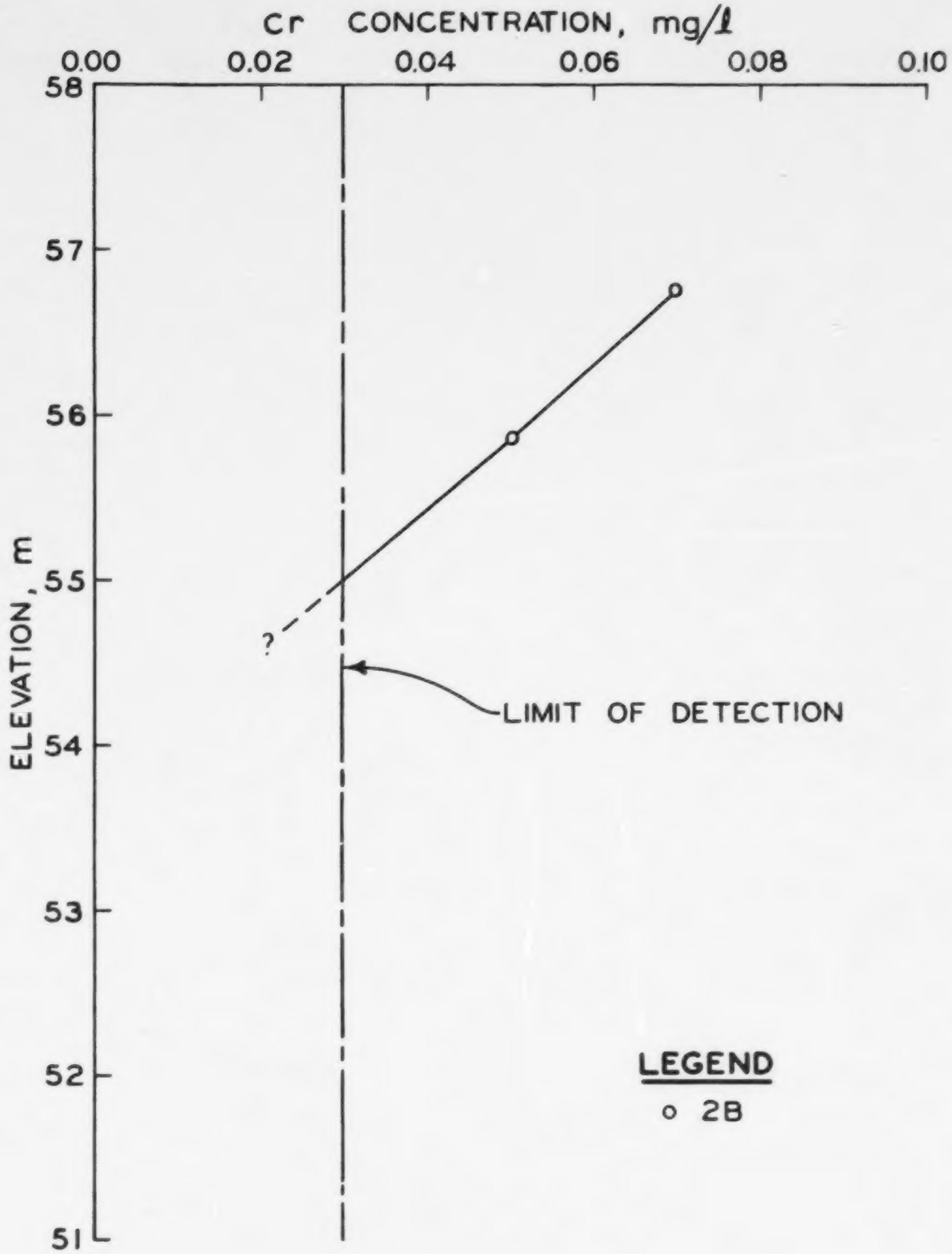


Figure 15. Variation of chromium concentration in distilled water extracts of soil/sediment samples with elevation in boring 2 at site B.

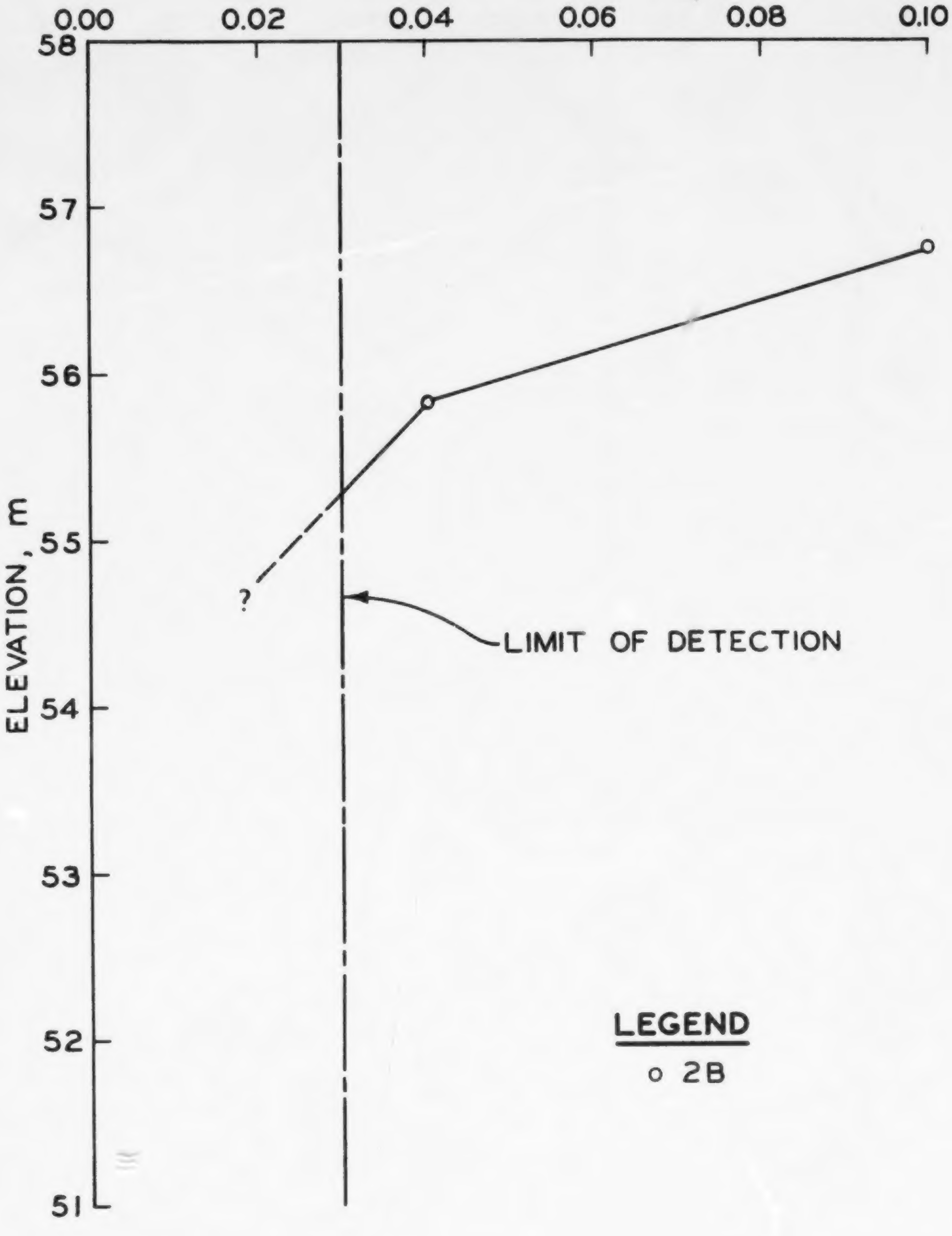


Figure 16. Variation of zinc concentration in distilled water extracts of soil/sediment samples with elevation in boring 2 at site B.

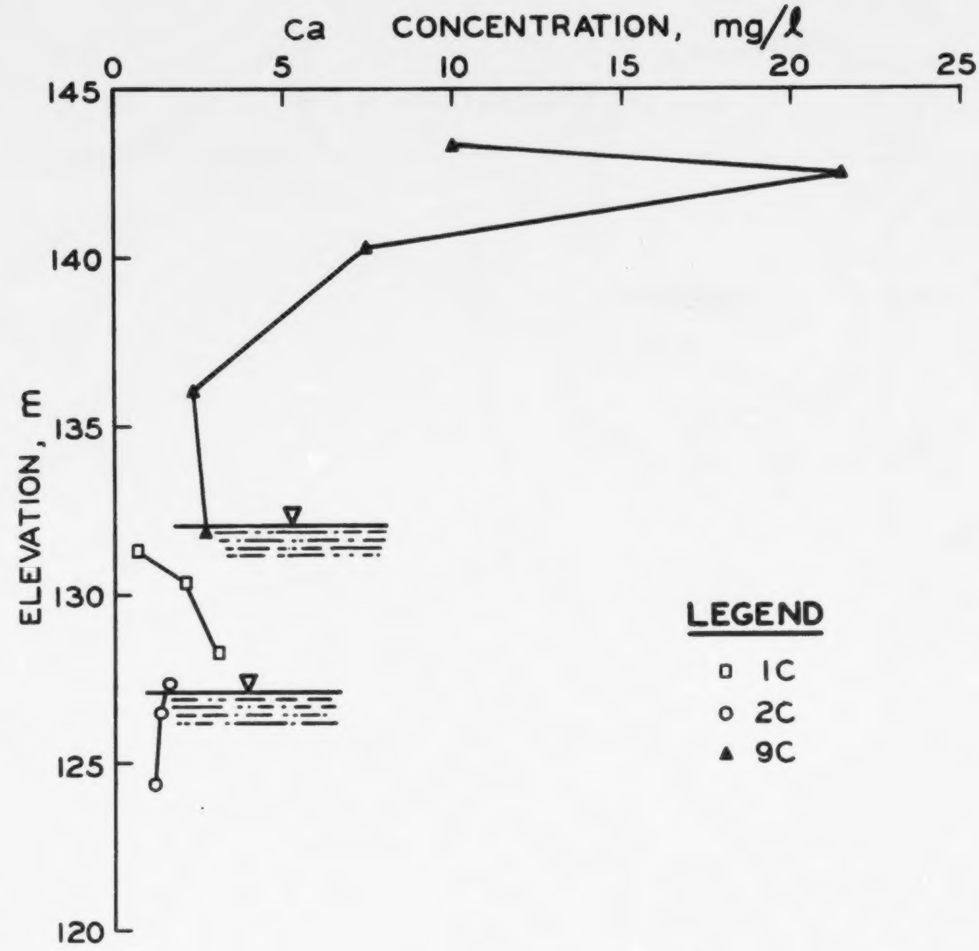


Figure 17. Variation of calcium concentration in distilled water extracts of soil/sediment samples with elevation in borings 1, 2, and 9 at site C. Inverted triangle symbols indicate water table in each boring.

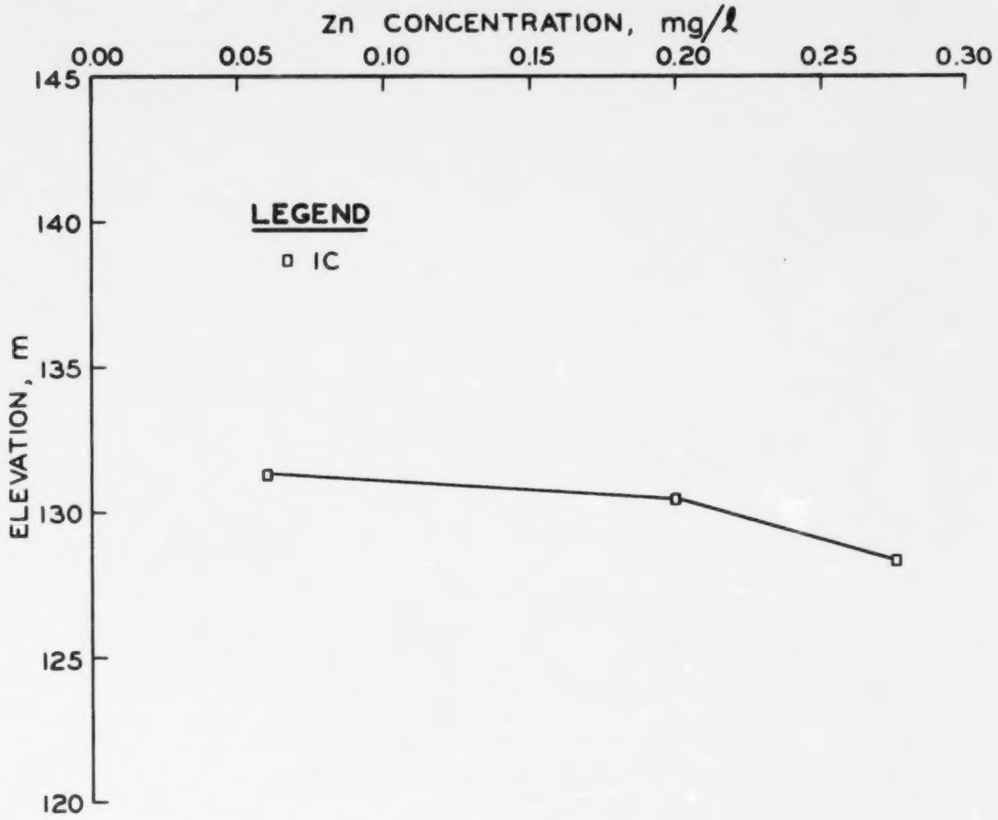


Figure 18. Variation of zinc concentration in distilled water extracts of soil/sediment samples with elevation in boring 1 at site C.

At site B, significant positive correlations with sample elevation were observed with cyanide, total organic carbon, iron, sodium, boron, chromium, and zinc. A positive correlation is expected for constituents derived from the landfill. The control holes showed significant correlations with depth only for total organic carbon and sodium. Both of these correlations were negative indicating these constituents were being leached away in a normal weathering situation.

Calcium at site B showed a significant negative correlation with sample elevation in borings under the landfill. Calcium is probably being leached away or is forming less soluble compounds under the landfill. In control holes both significant positive and negative correlations with depth are found.

At site C, zinc showed a significant negative correlation with elevation under the landfill indicating that it is becoming more available with increasing depth. Control holes indicated no significant relationship in zinc content between water extracts and elevation. Calcium showed a positive correlation with elevation in one of the holes through the landfill and a nagative correlation in a second hole indicating there may be both an increase and decrease in clacium availability under the landfill. This may be due to the variation in the age or character of refuse placed in different parts of the landfill. No significant relationship between sample depth and calcium concentration in water extracts could be seen in the control holes.

Patterns observed in the composition of distilled water extracts for samples taken from these landfill areas indicate that the availability of total organic carbon, iron, sodium, boron, and chromium to contacting waters increases under a landfill. The availability of calcium generally decreases under the landfill at site C.

Griffin and others (15) demonstrated that municipal leachate can remove calcium from clays. Calcium was the major exchangeable cation present in the clays used in their experimental leachate attenuation system and was displaced by other cations from the leachate such as sodium, or ammonium ion. The calcium level was higher in the effluent coming out of the clays than in the original leachate. Municipal leachate is mildly acid and contains carbon dioxide in solution. Calcium in the soil in the form of carbonate could be taken directly into solution by the leachate and removed from the soil below the refuse.

Horizontal Variation in Distilled Water Extracts of Sediment/Soil Samples Near the Water Table

According to the model for leachate movement under a landfill (Figure 1) horizontal movement of contaminants takes place below the water table. The model suggests that upgradient samples should have low levels of contamination. The highest levels of contamination should occur below the landfill, and a gradual decrease should occur down the groundwater gradient from the landfill. The decrease in contaminant concentration is related to the dilution effects of the groundwater and the filtration and adsorption in the soil/sediment. The distilled water extracts measure availability of the chemical constituents to contacting water. The concentration of any constituent in the distilled water extract depends not only on the amount of contaminant present; but also on the solubility of the contaminant under the pH and redox conditions present in the soil/sediment sample. Chemical analyses of distilled water extracts of soil samples collected near the existing water table were examined to determine if any pattern of contaminant distribution in the extracts could be related to the direction of movement of groundwater.

The number of samples available at each site was too small to allow the use of analysis of variance. Graphs showing concentration of various constituents versus relative position of the boring with respect to the landfill are given in Figures 19-21.

At site A, maximum levels for sulfate, nitrite, total organic carbon (TOC), calcium, magnesium, sodium, arsenic, cadmium, nickel and zinc occurred in distilled water extracts taken from samples under the landfill. The amounts available decreased down the groundwater flow gradients. This is the pattern expected for materials added from the refuse. Manganese levels were below detection limits under the landfill at site A and increased downgradient from the landfill. The unusually low levels of manganese below the landfill may be related to its chemical reduction to the soluble manganous ion and its loss into water percolating through the soil.

At site B, maximum levels for sulfate, cyanide, TOC, iron, manganese, boron and chromium were observed in distilled water leaches from samples taken under the landfill. Chloride showed a maximum level in a boring located upgradient from the fill. Chloride may be depleted under the fill due to slightly increased infiltration through the refuse. Calcium, magnesium, sodium, nickel, lead, and zinc showed maximum levels in the distilled water leaches in downgradient wells. The maxima observed in downgradient wells may represent materials transported in the groundwater and deposited in surrounding soil.

At site C, the maximum levels for nitrate, TOC, calcium, iron, magnesium, manganese, sodium, and boron were all found in extracts from borings down the groundwater gradient from the landfill. No maxima were found under the landfill. Lead and zinc were both more concentrated in distilled water leaches from sediment/soil samples obtained from upgradient borings. The high levels in downgradient holes may represent materials displaced from the landfill and moved downgradient. Lead and zinc may have been made less soluble in the sub-landfill and downdip holes by precipitation in some insoluble form such as sulfide.

There is evidence at sites B and C of displacement of materials from the area under the refuse down the groundwater flow gradient. In slow flow through a porous medium such as sediment/soil, some separation of constituents can be expected due to differing affinities for the solid phases present (clays, carbonates, etc.) and participation in solution/precipitation reactions. Zones of high concentrations of various contaminants (as seen in water extractions) may be displaced by this type of chromatographic activity. Recharge events such as heavy rainfall at the landfill may further add to the uneven pattern observed in contaminant distribution. The sulfides associated with some of

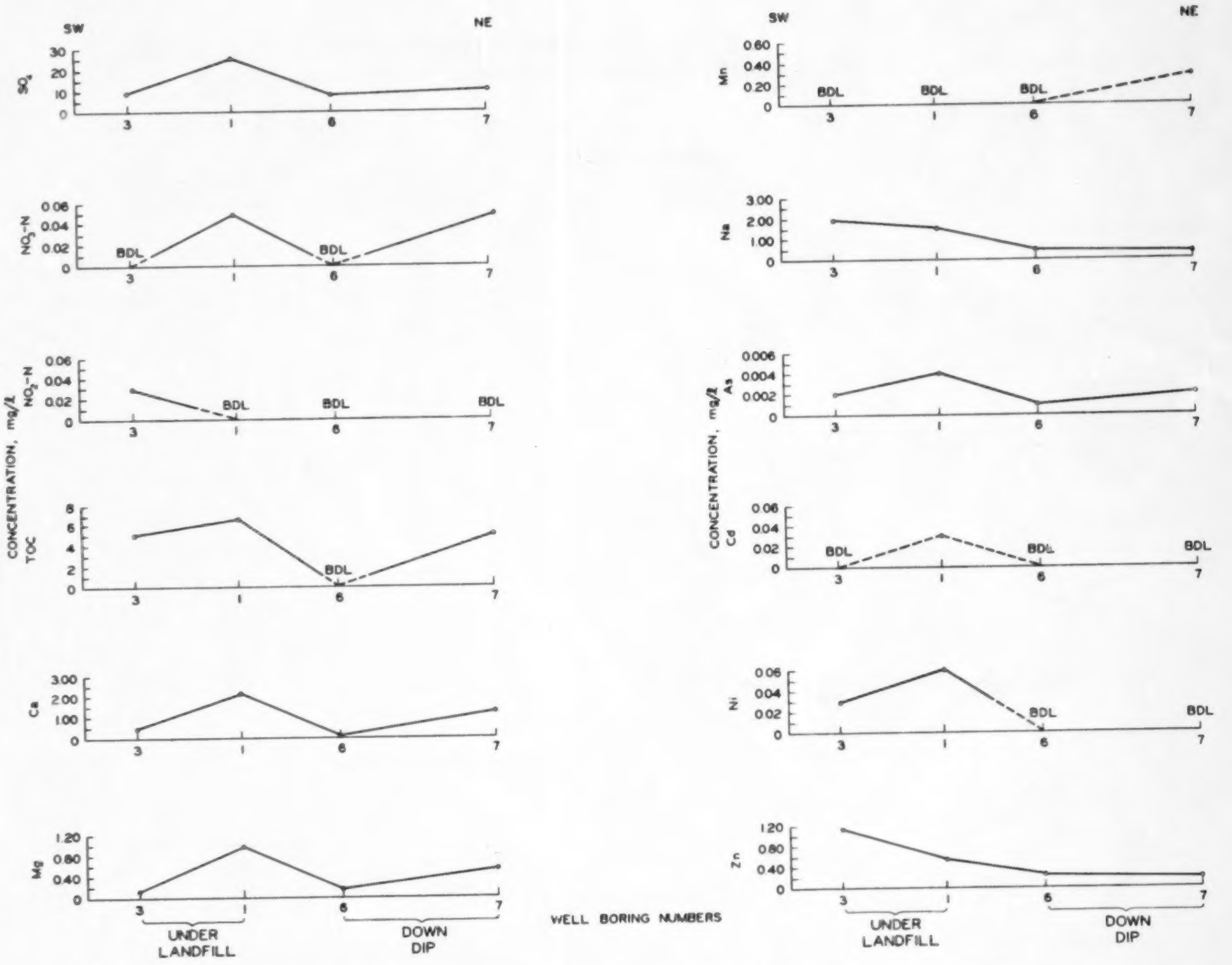


Figure 19. Horizontal variation in chemical composition of distilled water extracts at site A. BDL indicates below detection limits.

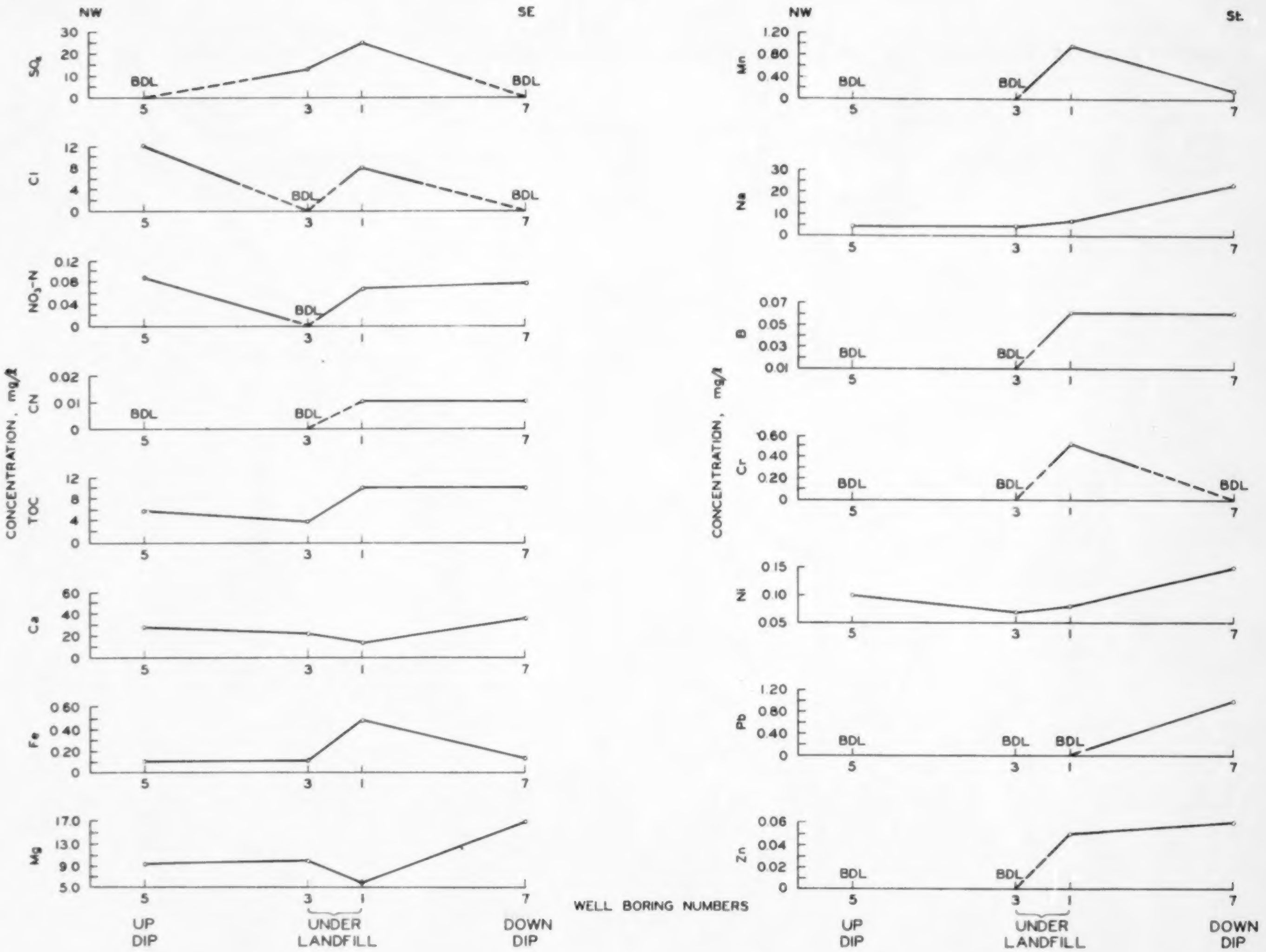


Figure 20. Horizontal variation in chemical composition of distilled water extracts at site B. BDL indicates below detection limits.

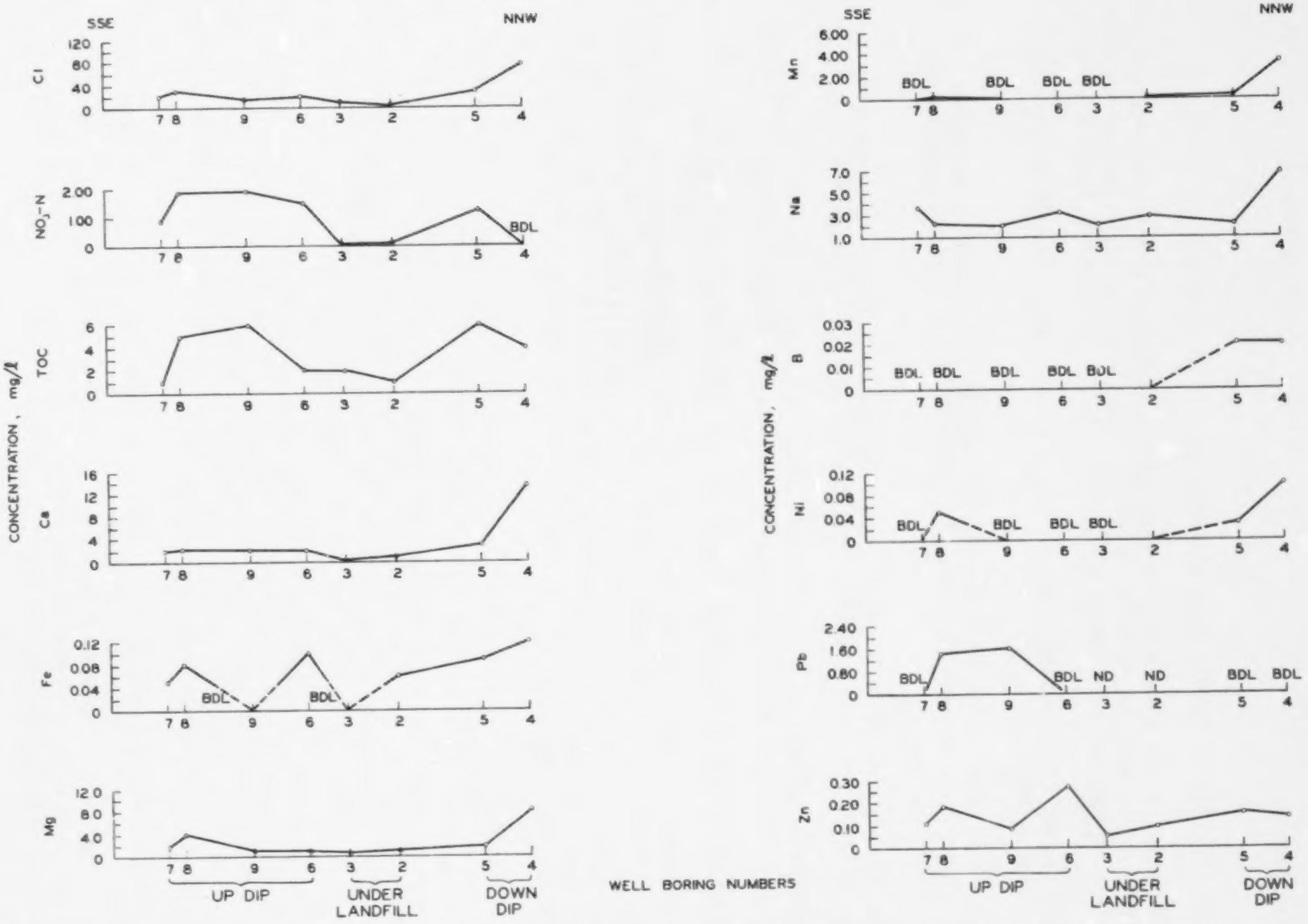


Figure 21. Horizontal variation in chemical composition of distilled water extracts at site C. BDL indicates below detection limits.

the landfills may also reduce the level of some metals in water extracts below the concentrations found in sediment/soil samples up the groundwater gradient from the landfill.

CHEMICAL ANALYSES OF NITRIC ACID EXTRACTS

The goal of the nitric acid digest was to determine the concentration of pollutants that could be released under the most extreme conditions of weathering. The concentration of materials in the nitric acid digest depends upon:

a) the original constituents in the soil and their reactivity with the hot acid,

b) the extent to which water-soluble and leachate-soluble materials have been removed from the soil by solution in rainwater or leachate, and,

c) the solubility in acid of materials which have been precipitated, filtered or absorbed from the leachate passing through the soil.

The analyses of nitric acid digests are given in Tables 25-30. The analytical results are expressed in milligrams per kilogram dry weight of sample.

Comparison of Nitric Acid Digests from Beneath and Outside the Landfills

Soil samples from directly below the landfill (experimental samples) and samples taken at comparable depths outside the landfill (control samples) were digested in nitric acid and the digests were analyzed for selected cations. Care was taken to select samples outside the landfill that were above the water table so that the samples were not contaminated by horizontal movement of leachate from the landfill.

A randomization test was used to evaluate the significance of any differences in means observed between experimental samples and control samples. This procedure was used to avoid the assumption of normal distribution and homogeneous variance required by the more commonly used t-test. With the small sample size, five samples at each site, the highest level of significance that could be assigned to a two-tailed, randomization test was 80%. The results of the randomization tests are presented in Table 31.

In the majority of cases, the nitric acid digests of soil samples from below the landfills showed higher metal content than the nitric acid digest of soil outside the landfills. The increased metal content in the soil represents material filtered, absorbed or precipitated from the leachate (i.e. attenuated) on its contact with the sub-landfill soil.

At site A, significant differences in concentration in the acid digests of samples beneath and outside the landfill occurred with arsenic, boron, beryllium, nickel and selenium. Boron and beryllium showed higher concentrations in the nitric acid digests from samples taken from below the landfill. The levels of arsenic, nickel and selenium in the sub-landfill soil were

TABLE 25. ANALYSES OF NITRIC ACID DIGESTS OF SOIL SAMPLES FROM EXPERIMENTAL BORINGS AT SITE A

Boring and sample	1C1	1C2	1C3	1C4	1C5	1C6	1C7	2C1	2C2	2C3
Elev (m)	250.57	249.77	247.58	242.08	234.81	230.83	230.83	250.98	250.14	247.99
Depth below mw/soil interface (m)	0.00	0.82	3.02	8.52	15.78	19.77	19.77	0.00	0.84	2.99
Ht above water table (m)	18.06	17.24	15.05	9.55	2.28	-1.70	-1.70	19.97	19.13	16.98
Conc. (mg/kg dry wt)										
Fe	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Mn	302.25	399.52	444.63	462.02	593.04	287.36	320.14	894.94	374.26	579.75
As	0.10	0.17	0.15	0.14	0.14	0.22	0.17	0.16	0.14	0.14
B	2.90	4.10	3.54	2.99	2.10	2.87	1.60	2.07	1.29	1.63
Be	0.07	0.11	0.08	0.09	0.11	0.30	0.09	0.08	0.06	0.07
Cd	0.27	0.42	0.35	0.49	0.41	0.47	0.36	0.29	0.28	0.30
Cr	2.96	2.73	3.13	2.85	2.58	5.75	2.02	2.96	1.94	2.90
Cu	8.06	6.52	8.65	7.34	9.95	10.54	6.74	9.77	5.42	10.99
Hg	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Ni	5.04	5.57	6.01	6.79	5.93	6.70	4.38	5.23	4.00	5.80
Pb	25.19	17.87	26.35	16.31	21.04	28.74	21.90	11.34	12.26	8.48
Se	0.32	0.46	0.53	0.68	0.44	0.50	0.39	0.26	0.40	0.34
Zn	17.95	10.93	10.54	7.88	7.36	11.97	8.17	7.44	6.13	7.97

(continued)

TABLE 25. (continued)

Boring and sample	2C4	2C5	2C6	3C1	3C2	3C3	3C4	3C5	3C6
Elev (m)	243.00	237.11	232.08	250.53	249.53	247.60	240.27	235.72	230.73
Depth below mw/soil interface (m)	7.99	13.87	18.90	0.00	1.00	2.93	10.26	14.81	19.80
Ht. above water table (m)	11.99	6.10	1.07	19.31	18.31	16.38	9.05	4.50	-0.49
Conc. (mg/kg dry wt)									
Fe	ND	ND	ND	ND	ND	ND	ND	ND	ND
Mn	340.26	618.55	366.97	312.12	1015.93	741.15	410.14	356.57	209.50
As	0.14	0.16	0.16	0.16	0.47	0.40	0.26	0.28	0.19
B	1.24	1.29	0.86	1.35	1.39	1.50	0.75	0.84	1.00
Be	0.06	0.06	0.10	0.11	0.08	0.07	0.06	0.06	0.05
Cd	0.24	0.30	0.22	0.33	0.32	0.32	0.27	0.28	0.22
Cr	2.27	2.45	1.65	2.48	2.99	3.44	2.61	2.34	1.86
Cu	6.80	10.44	8.13	7.38	7.17	9.75	8.70	9.02	7.86
Hg	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Ni	4.76	5.54	4.16	5.25	5.84	6.24	5.59	4.90	4.00
Pb	9.64	11.60	10.40	12.77	11.83	11.70	12.43	10.03	9.05
Se	0.27	0.30	BDL	0.31	0.31	0.32	0.31	0.28	0.27
Zn	6.24	12.50	6.18	36.18	54.97	7.80	6.84	6.68	10.23

BDL = Below detection limits.

ND = Not determined.

TABLE 26. ANALYSES OF NITRIC ACID DIGESTS OF SOIL SAMPLES FROM CONTROL BORINGS AT SITE A

Boring and sample	6C1	6C2	6C3	6C4	6C5	6C6	7C1	7C2	7C3	7C4	7C5	7C6
Elev (m)	251.09	250.20	248.08	242.05	236.86	230.84	250.49	250.15	247.99	242.23	236.37	233.32
Ht. above water table (m)	19.99	19.10	16.98	10.95	5.76	-0.26	14.97	14.63	12.47	6.71	-0.85	-2.20
Conc. (mg/kg dry wt)												
Fe	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Mn	566.29	503.83	546.34	417.92	632.26	295.05	447.30	561.80	986.56	810.06	72.08	96.42
As	0.51	0.64	0.60	0.49	0.55	0.50	0.41	0.50	0.75	0.51	0.26	0.24
B	1.08	1.08	1.34	0.82	0.86	0.72	0.95	1.24	1.50	1.29	0.79	0.56
Be	0.06	0.07	0.07	0.07	0.07	0.05	0.07	0.06	0.06	0.07	0.04	0.05
Cd	0.27	0.27	0.27	0.29	0.28	0.19	0.31	0.33	0.27	0.35	0.30	0.24
Cr	2.95	3.32	3.46	2.88	3.23	1.79	2.78	3.66	7.52	3.86	0.92	0.81
Cu	7.83	9.76	10.26	9.59	11.46	6.75	7.05	9.21	12.45	12.02	0.92	1.67
Hg	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Ni	5.72	6.38	6.07	6.17	6.45	3.84	5.96	6.73	7.28	7.91	1.44	1.41
Pb	8.43	10.85	8.92	9.59	9.87	7.15	11.52	12.41	8.93	12.22	6.55	6.00
Se	0.36	0.36	0.31	0.30	0.32	0.25	0.36	0.27	0.34	0.29	0.43	0.46
Zn	7.59	8.54	17.28	8.22	9.48	4.52	6.78	10.06	9.67	10.22	2.29	1.71

Note: All borings are positioned downdip on the groundwater gradient.

BDL = Below detection limits.

ND = Not determined.

TABLE 27. ANALYSES OF NITRIC ACID DIGESTS OF SOIL SAMPLES FROM EXPERIMENTAL BORINGS AT SITE B

Boring and sample	1C1	1C2	2C1	2C2	2C3	3C1	3C2	3C3
Elev (m)	55.93	54.06	56.77	55.85	53.72	56.74	55.74	53.50
Depth below mw/soil interface (m)	0.00	1.87	0.00	0.92	3.05	0.00	1.00	3.24
Ht above water table (m)	1.57	-0.30	5.83	4.91	2.78	5.51	2.51	0.27
Conc. (mg/kg dry wt)								
Fe	18007.	15241.	14425.	15552.	11351.	17246.	10028.	12099.
Mn	945.76	1443.93	559.55	450.69	342.08	505.12	343.56	306.60
As	4.81	4.30	5.25	3.84	2.10	4.43	1.75	1.19
B	5.63	4.53	6.96	6.57	5.14	8.66	5.39	6.78
Be	1.05	1.03	1.76	1.74	1.41	1.70	1.57	1.56
Cd	0.15	0.54	0.23	0.21	0.15	0.43	0.19	0.13
Cr	8.78	7.49	7.46	9.19	7.60	8.08	7.83	7.60
Cu	13.47	12.30	11.31	9.61	8.68	11.55	10.16	11.47
Hg	0.08	0.08	0.04	0.03	0.02	0.04	0.05	0.03
Ni	21.56	22.26	29.23	21.70	17.87	22.37	20.38	25.33
Pb	10.59	9.36	58.46	8.30	7.19	8.66	7.76	7.60
Se	2.95	2.95	2.20	1.52	1.28	1.80	1.94	1.65
Zn	50.54	61.23	54.28	45.97	38.47	57.72	40.11	39.28

TABLE 28. ANALYSES OF NITRIC ACID DIGESTS OF SOIL SAMPLES FROM CONTROL BORINGS AT SITE B

Boring and sample	5C1	5C2	5C3	6C1	6C2	6C3	7C3
Elev (m)	55.28	54.38	52.44	54.26	53.35	51.22	42.00
Ht. above water table (m)	1.93	1.03	-0.91	4.11	3.20	1.07	0.10
Position in groundwater gradient	updip	updip	updip	updip	updip	updip	downdip
Conc. (mg/kg dry wt)							
Fe	13054.	11336.	13214.	12924.	13486.	8692.	4062.
Mn	497.27	352.03	233.26	428.78	445.18	113.75	2784.25
As	3.95	3.04	2.46	3.04	3.41	0.89	BDL
B	7.32	5.55	5.78	5.12	5.54	3.68	73.73
Be	1.77	1.52	1.51	1.46	1.80	1.26	1.20
Cd	0.26	0.18	0.16	0.20	0.22	0.25	0.21
Cr	7.80	6.62	9.79	6.64	8.48	8.00	15.00
Cu	9.88	9.72	9.57	8.01	9.13	9.04	23.25
Hg	0.06	0.04	0.03	0.02	0.03	0.03	BDL
Ni	29.72	24.58	24.29	23.77	26.90	21.86	32.12
Pb	7.73	7.75	7.49	7.60	7.97	6.95	39.54
Se	3.00	2.03	1.12	1.52	0.94	1.44	BDL
Zn	42.68	39.26	37.77	35.83	48.00	35.91	42.23

TABLE 29. ANALYSES OF NITRIC ACID DIGESTS OF SOIL SAMPLES FROM EXPERIMENTAL BORINGS AT SITE C

Boring and sample	1C1	1C2	1C3	2C1	2C2	2C3	3C1	3C2	3C3
Elev (m)	131.41	130.48	128.34	127.46	126.55	124.41	125.50	124.57	123.20
Depth below mw/soil interface (m)	0.00	0.93	3.07	0.00	0.91	3.05	0.00	0.93	2.30
Ht. above water table (m)	4.40	3.47	1.33	0.20	-0.71	-2.85	2.48	1.55	0.18
Conc. (mg/kg dry wt)									
Fe	25871.0	24824.	23065.	22119.	28710.	24573.	27563.	24723.	36287.
Mn	869.23	585.91	431.75	386.14	642.77	339.37	710.84	409.30	84.28
As	0.52	0.72	0.48	0.52	0.72	0.52	0.76	0.77	0.73
B	226.31	230.89	217.17	209.19	235.07	207.82	232.60	210.14	292.87
Be	1.36	1.36	1.89	2.03	1.47	1.27	0.90	0.79	1.94
Cd	2.08	2.22	2.12	2.24	1.93	1.77	2.00	1.74	2.92
Cr	19.29	21.82	16.79	15.42	10.65	9.59	9.38	16.13	11.36
Cu	40.22	34.17	45.87	55.36	42.36	41.56	11.12	31.11	17.71
Hg	0.03	0.05	0.02	0.03	0.03	0.05	0.04	0.04	0.03
Ni	28.29	29.10	36.13	33.94	32.93	34.03	10.40	15.60	14.79
Pb	21.71	21.35	18.71	23.51	22.83	17.08	18.09	17.86	18.79
Se	0.57	0.50	0.39	0.37	0.39	0.16	0.16	0.37	0.31
Zn	60.07	66.07	78.78	96.69	91.21	85.41	31.38	35.30	55.79

TABLE 30. ANALYSES OF NITRIC ACID DIGESTS OF SOIL SAMPLES FROM CONTROL BORING AT SITE C

Boring and sample	6C1	6C2	6C3	6C4	6C5	7C4	8C3	9C1	9C2	9C3	9C4	9C5	4C6	5C4
Elev (m)	132.46	131.54	129.41	127.88	126.06	121.80	130.14	143.47	142.57	140.44	136.17	131.91	124.74	126.92
Ht. above water table (m)	5.42	4.50	2.37	0.84	-0.98	0.09	-0.36	11.47	10.57	8.44	4.17	-0.09	-0.66	-0.12
Position in groundwater gradient	Updip	Updip	Updip	Updip	Updip	Updip	Updip	Updip	Updip	Updip	Updip	Updip	Downdip	Downdip
Conc. (mg/kg dry wt)														
Fe	17938.	22378.	12745.	30634.0	12124.7	18140.	15277.	21340.	20419.	23658.	22352.	15584.	23137.	12719.
Mn	46.21	13.90	20.85	160.59	194.73	121.83	231.70	118.74	71.71	110.27	210.50	76.39	655.94	149.64
As	1.12	0.97	0.49	0.75	0.54	0.81	0.53	1.14	0.89	0.41	0.57	0.79	0.72	1.49
B	180.68	337.89	141.55	298.24	102.35	137.00	116.13	180.03	182.31	205.84	211.94	122.23	182.29	107.47
Be	0.54	0.66	1.05	2.26	0.84	0.95	1.97	0.69	1.05	0.89	1.10	0.92	1.39	1.12
Cd	1.89	3.10	1.60	2.96	2.08	2.12	1.90	2.10	2.28	2.55	2.42	2.14	2.30	1.50
Cr	14.10	19.28	7.87	9.99	10.60	15.54	7.72	14.01	10.63	14.63	8.39	5.02	13.79	14.2
Cu	11.50	17.67	24.14	46.33	15.22	21.93	15.28	18.99	49.95	51.26	29.37	16.58	37.63	63.12
Hg	0.03	0.06	0.05	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.07	0.02
Ni	6.63	7.64	14.70	32.30	19.11	25.50	13.25	9.47	14.28	7.42	7.01	5.00	31.78	21.42
Pb	11.37	15.12	11.98	22.67	14.07	12.56	13.30	20.79	23.82	24.39	18.24	7.94	26.64	11.09
Se	0.24	0.19	0.23	0.21	0.30	0.15	0.16	0.11	0.17	0.25	0.25	0.30	0.16	0.29
Zn	21.25	24.53	30.01	81.42	49.13	89.89	47.52	17.56	17.74	16.77	13.09	11.31	85.69	67.34

TABLE 31. RESULTS OF RANDOMIZATION TEST ON NITRIC ACID DIGESTS OF SOIL SAMPLES DIRECTLY UNDER THE LANDFILLS AND AT COMPARABLE DEPTHS OUTSIDE THE LANDFILLS

Parameter	Site A	Site B	Site C
Fe	ND	S	S
Mn	NS	S	S
As	S	S	S
B	S	NS	S
Be	S	NS	S
Cd	NS	NS	NS
Cr	NS	NS	NS
Cu	NS	S	NS
Hg	N	NS	S
Ni	S	NS	S
Pb	NS	S	NS
Se	S	NS	NS
Zn	NS	S	S

S = Significant at 80% level.

NS = Not significant at 80% level.

ND = Not determined.

N = Not detected in any sample.

lowered possibly by leaching effects due to the organic acids and chemically reducing conditions produced by the landfill.

At site B, significant differences in concentrations in acid digests were found for iron, manganese, arsenic, copper, lead and zinc. All of these metals showed increased levels in soil beneath the landfill as would be expected from consideration of the model (Figure 1).

At site C, significant differences were found in the concentration of iron, manganese, arsenic, boron, beryllium, mercury, nickel and zinc. Only arsenic showed a decrease in concentration beneath the landfill. Arsenic is behaving at site C as it did at site A and is being depleted in the soil immediately below the landfill.

If the number of metals that are found in significantly higher quantities under a landfill is used as a rough index of attenuation, the sand and gravel at site A is definitely poorer in attenuation than is the loess clay at site B or the deep, residual soil at site C. The material at site A would have both poorer filtering qualities because of its larger grain size and lower adsorption properties because of the lack of clay minerals.

None of the metals determined was shown to have a significant increase in the sub-landfill samples at all three sites. Iron, manganese, boron, beryllium and zinc all showed significant accumulation below the landfills at two of the three sites. These differences in metal levels probably reflect the differing composition of leachates at the three sites.

Vertical Variation of Constituents in Nitric Acid Digests of Soil Samples

For those elements that did show a significant difference in means between sub-landfill samples and samples from comparable depths outside the landfill, a test was made for a significant relationship between the concentration of a particular cation and the sample elevation in the borings. The model of leachate movement requires that those materials derived from the refuse show a positive correlation with elevation in the borings through the landfill. Outside the landfill the concentration of these materials in a nitric acid digest would depend on the prevailing weathering processes. There could be a positive or negative correlation or no correlation at all between sample elevation and the concentration of metals. In the model situation soil constituents that are being dissolved by the landfill leachate should show a negative correlation with sample elevation for samples from under the landfill. Outside the landfill, these elements may or may not show any correlation with sample elevation depending on their response to local weathering processes.

The Spearman rank correlation coefficient was used to judge the strength of association because this technique could be used with small numbers of samples where the sample distribution is not known. The results of the Spearman rank correlation are given in Tables 32-34. Graphs of concentrations versus sample elevation for all cations that showed statistically significant correlations in experimental borings are given in Figures 22-34. Significant correlations in control holes are shown for contrast.

TABLE 32. CORRELATION OF CHEMICAL ANALYSES OF NITRIC ACID DIGESTS OF SOIL SAMPLES WITH SAMPLE ELEVATION AT SITE A

	Experimental			Control	
Boring No.	1	2	3	6	7
Mn	NS	NS	NS	NS	NS
As	NS	NS	NS	NS	NS
B	SP	SP	NS	SP	NS
Be	NS	NS	SP	NS	NS
Ni	NS	NS	NS	NS	NS
Se	NS	NS	NS	NS	NS

SP = Significant positive correlation at 95% level.

SN = Significant negative correlation at 95% level.

NS = Not significant.

TABLE 33. CORRELATION OF CHEMICAL ANALYSES OF NITRIC ACID DIGESTS OF SOIL SAMPLES WITH SAMPLE ELEVATION AT SITE B

	Experimental			Control	
Boring No.	1*	2**	3	5	6
Fe	--	NS	NS	NS	NS
Mn	--	SP	SP	SP	NS
As	--	SP	SP	SP	NS
Cu	--	SP	NS	SP	NS
Pb	--	SP	SP	NS	NS
Zn	--	SP	SP	SP	NS

SP = Significant positive correlation at 95% level.

SN = Significant negative correlation at 95% level.

NS = Not significant.

* = No critical confidence level available for this size sample.

** = Due to small sample sizes all tests of significance are at 80% confidence level.

TABLE 34. CORRELATION OF CHEMICAL ANALYSES OF NITRIC ACID DIGESTS OF SOIL SAMPLES WITH SAMPLE DEPTH AT SITE C

	Experimental			Control	
Boring No.	1	2	3	6	9
Fe	SP	NS	NS	NS	NS
Mn	SP	NS	SP	NS	NS
As	NS	NS	NS	NS	NS
B	NS	SP	NS	NS	NS
Be	NS	SP	NS	NS	NS
Hg	NS	NS	NS	NS	SP
Ni	SN	NS	NS	SN	SP
Zn	SN	SN	SN	SN	SP

SP = Significant positive correlation at 95% level.

SN = Significant negative correlation at 95% level.

NS = Not significant.

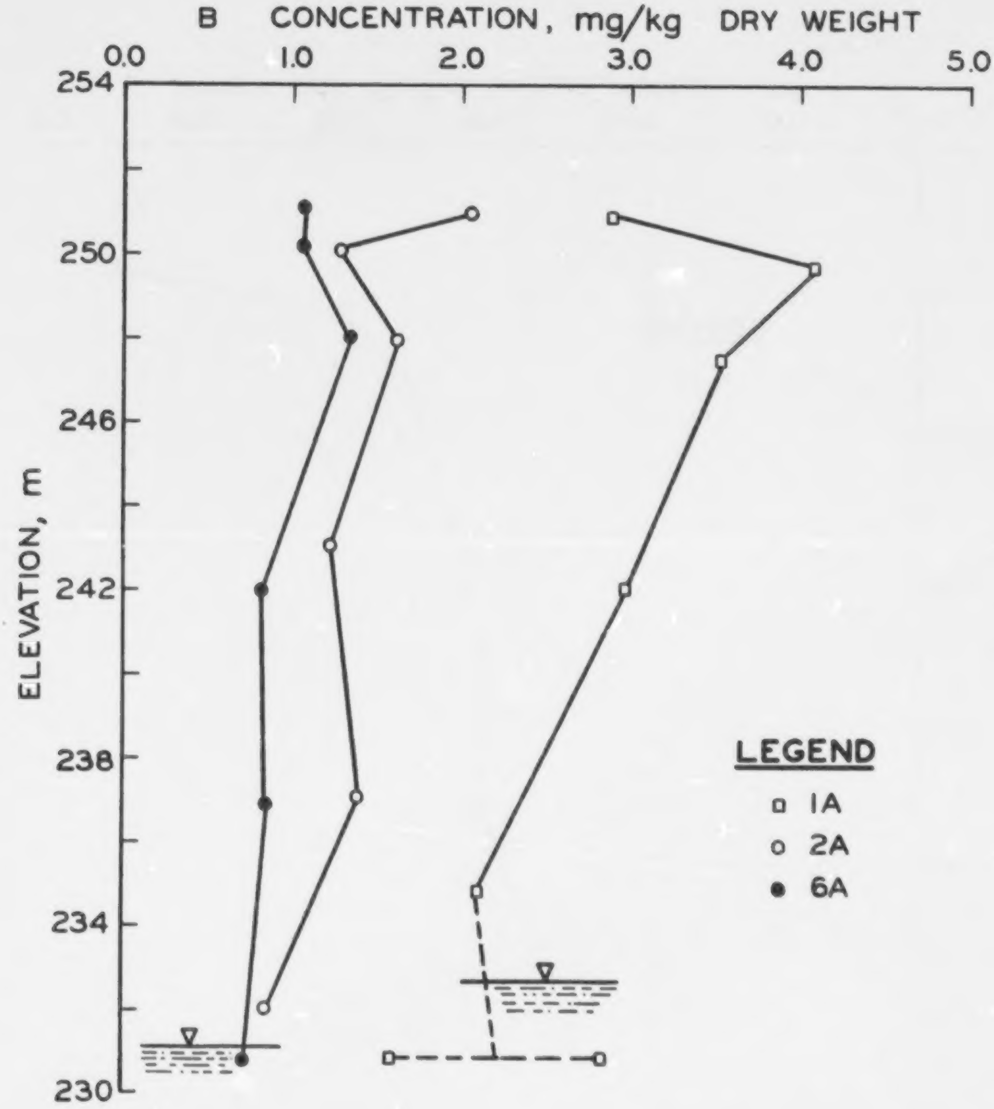


Figure 22. Variation of boron concentration in nitric acid digests of soil/sediment samples with elevation in borings 1, 2, and 6 at site A. Inverted triangle symbols indicate water table in each boring.

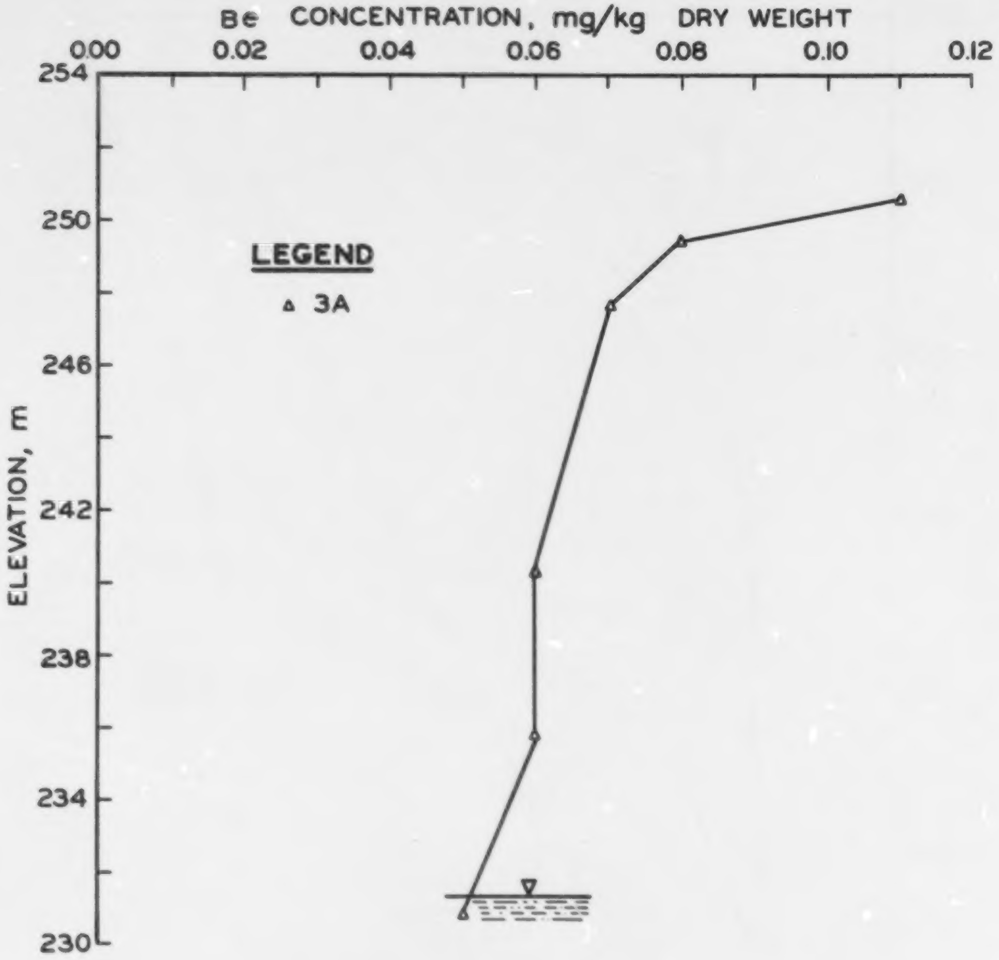


Figure 23. Variation of beryllium concentration in nitric acid digests of soil/sediment samples with elevation in boring 3 at site A. Inverted triangle symbol indicates water table.

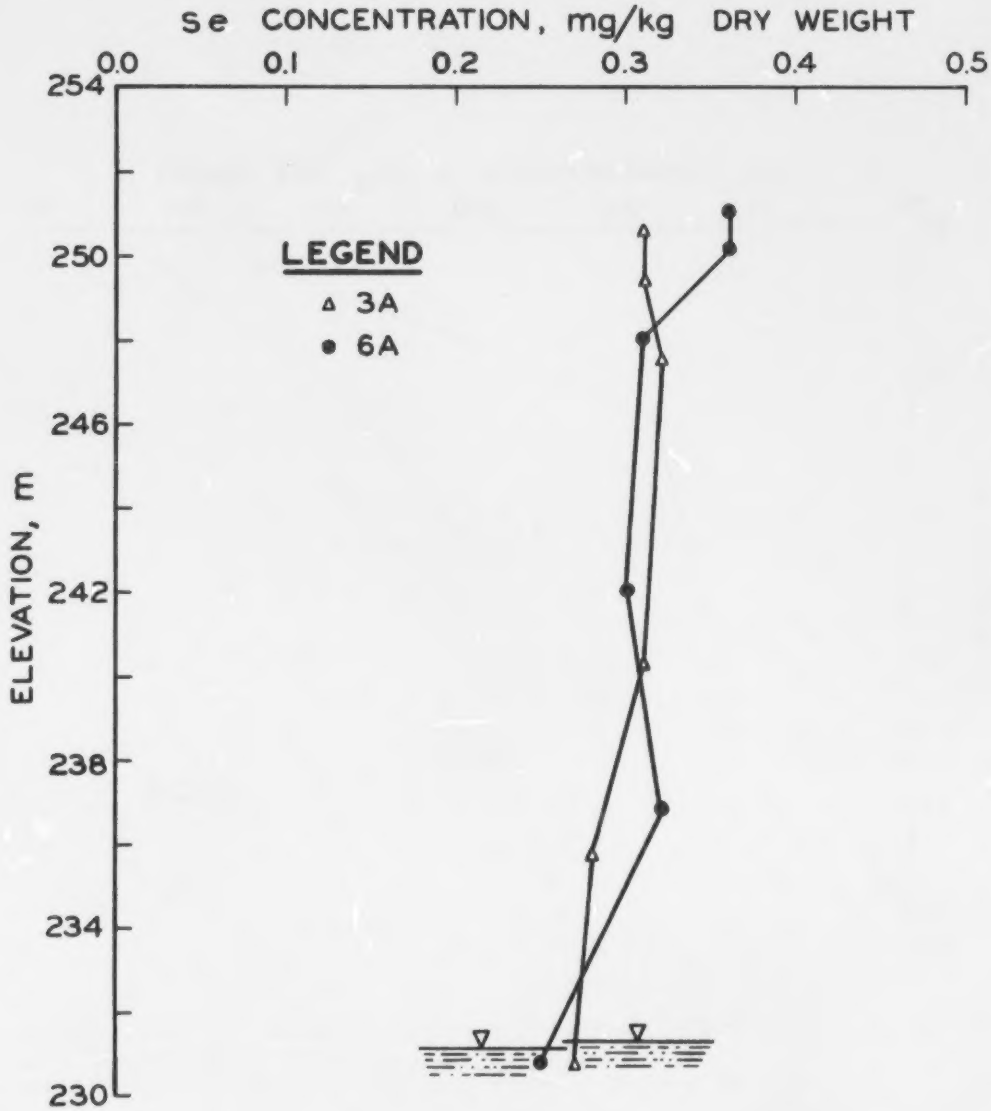


Figure 24. Variation of selenium concentration in nitric acid digests of soil/sediment samples with elevation in borings 3 and 6 at site A. Inverted triangle symbols indicate water table in each boring.

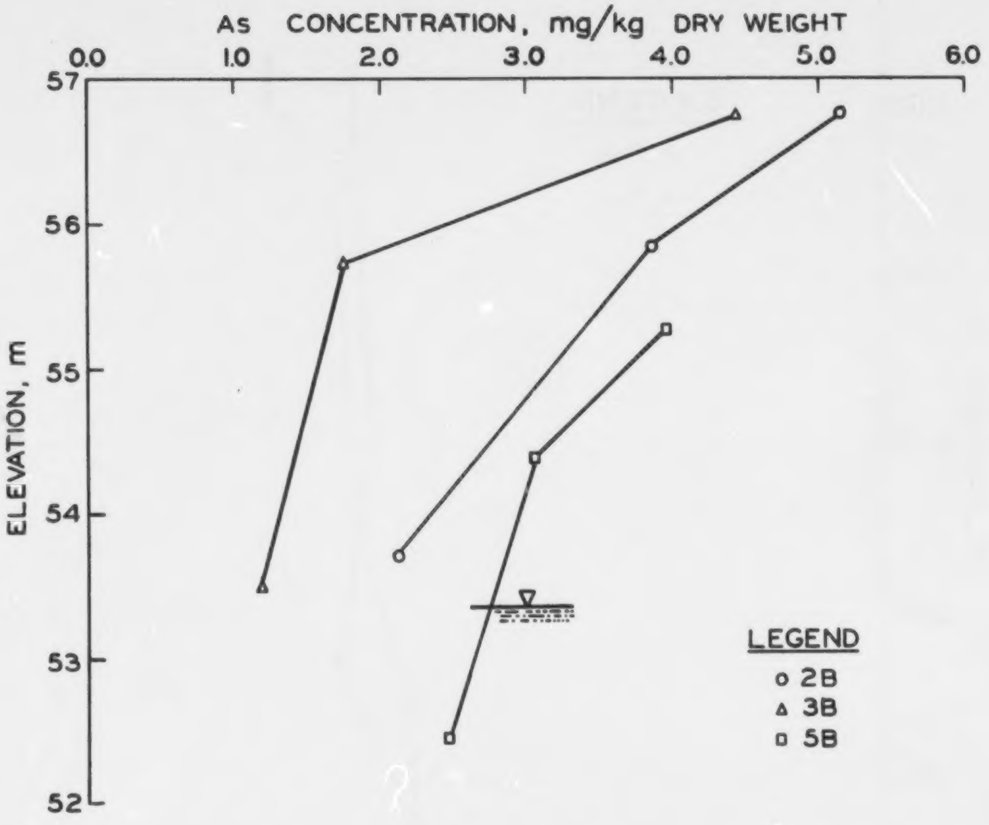


Figure 25. Variation of arsenic concentration in nitric acid digests of soil/sediment samples with elevation in borings 2, 3, and 5 at site B. Inverted triangle symbol indicates water table.

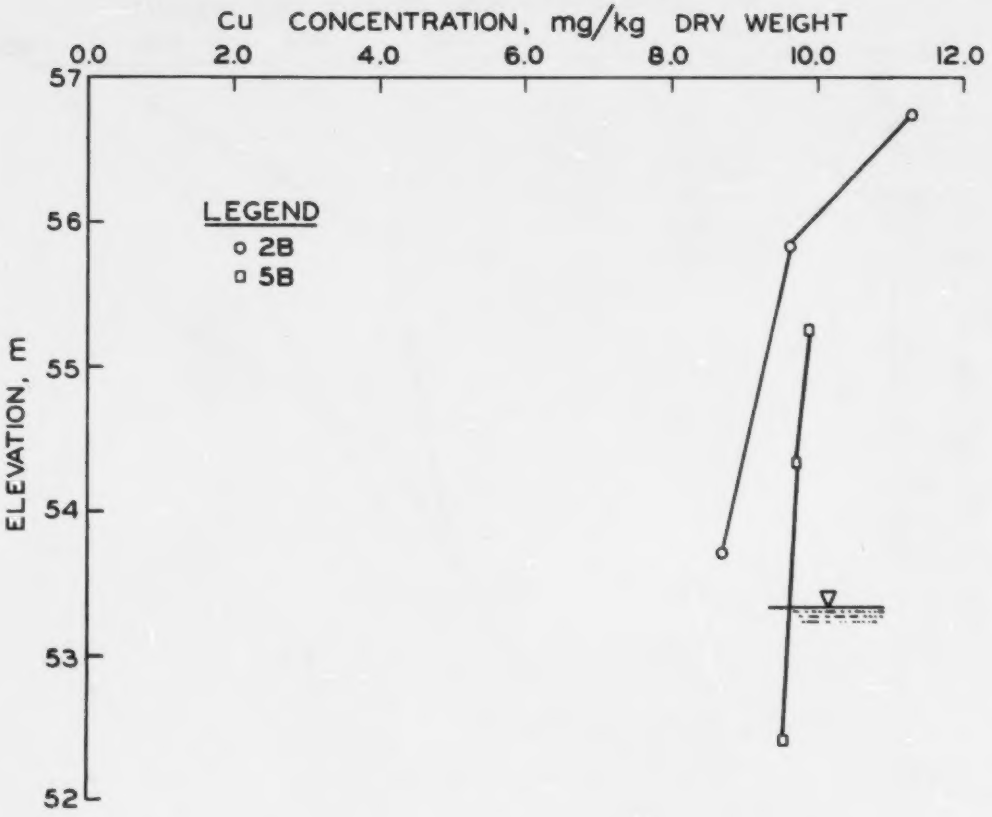


Figure 26. Variation of copper concentration in nitric acid digests of soil/sediment samples with elevation in borings 2 and 5 at site B. Inverted triangle symbol indicates water table.

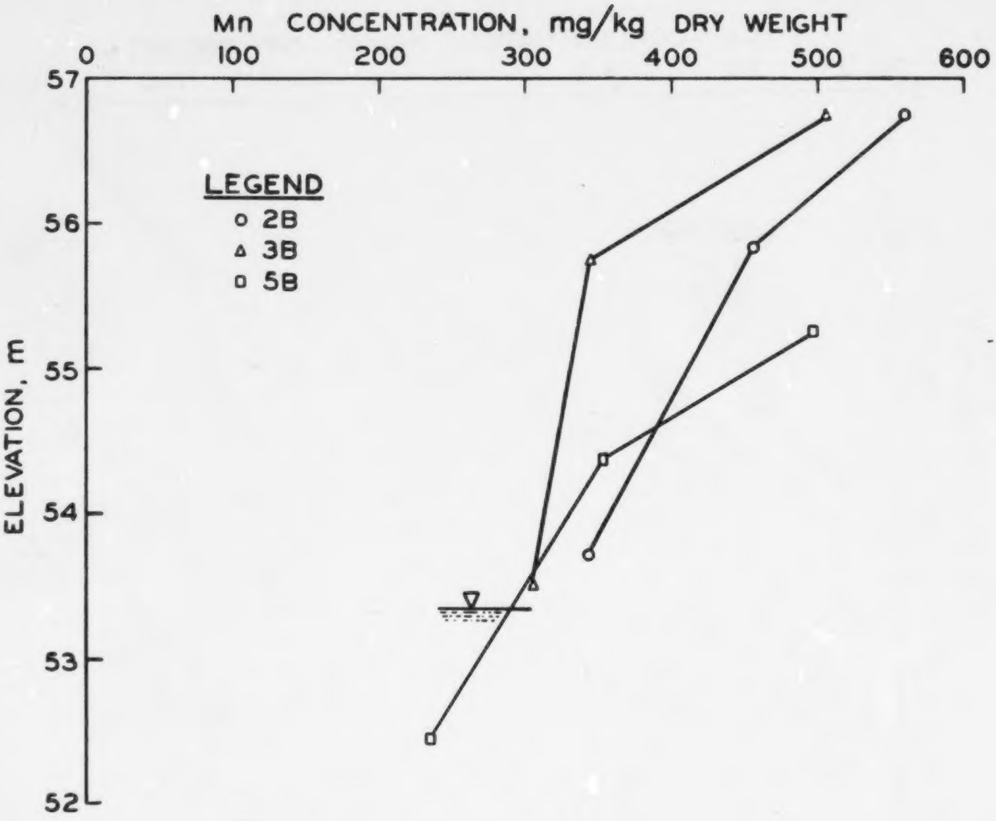


Figure 27. Variation in manganese concentration in nitric acid digests of soil/sediment samples with elevation in borings 2, 3 and 5 at site B. Inverted triangle symbol indicates water table.

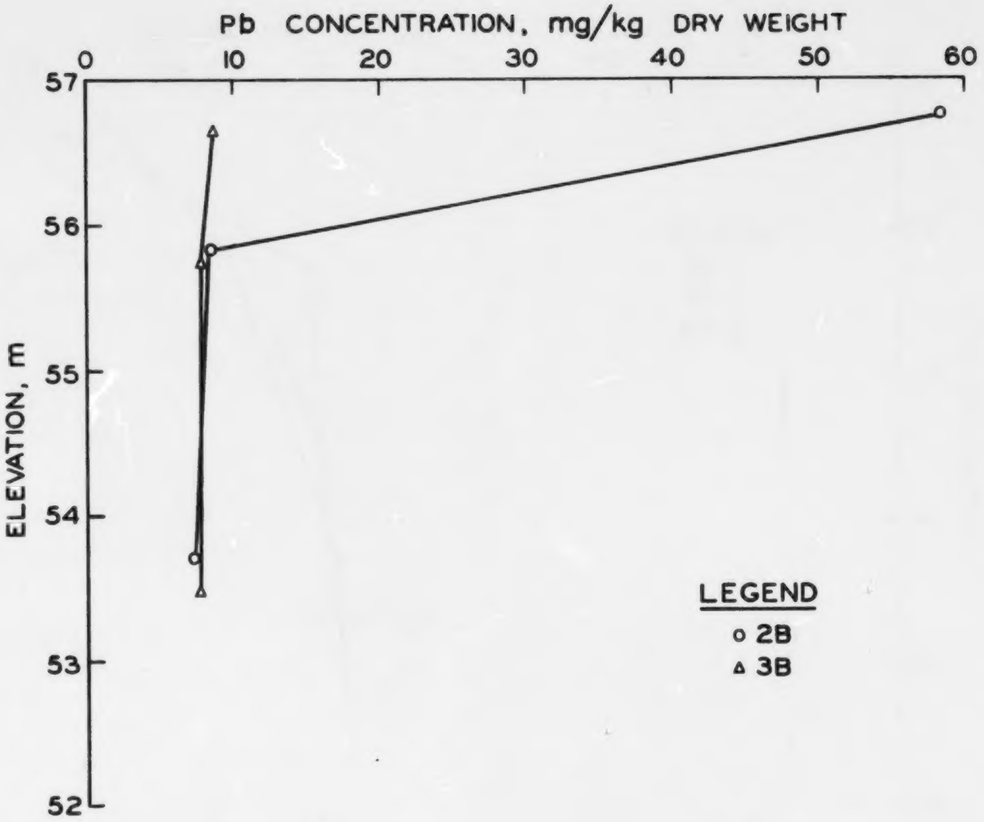


Figure 28. Variation of lead concentration in nitric acid digests of soil/sediment samples with elevation in borings 2 and 3 at site B.

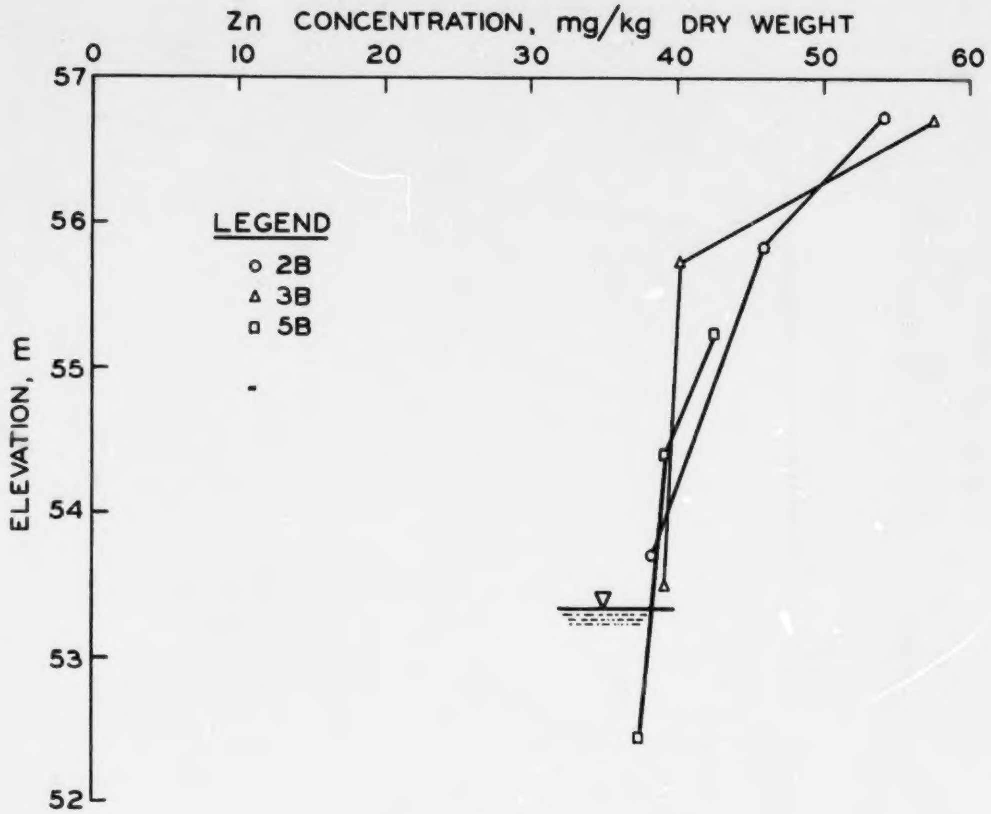


Figure 29. Variation of zinc concentration in nitric acid digests of soil/sediment samples with elevation in borings 2, 3, and 5 at site B. Inverted triangle symbol indicates water table.

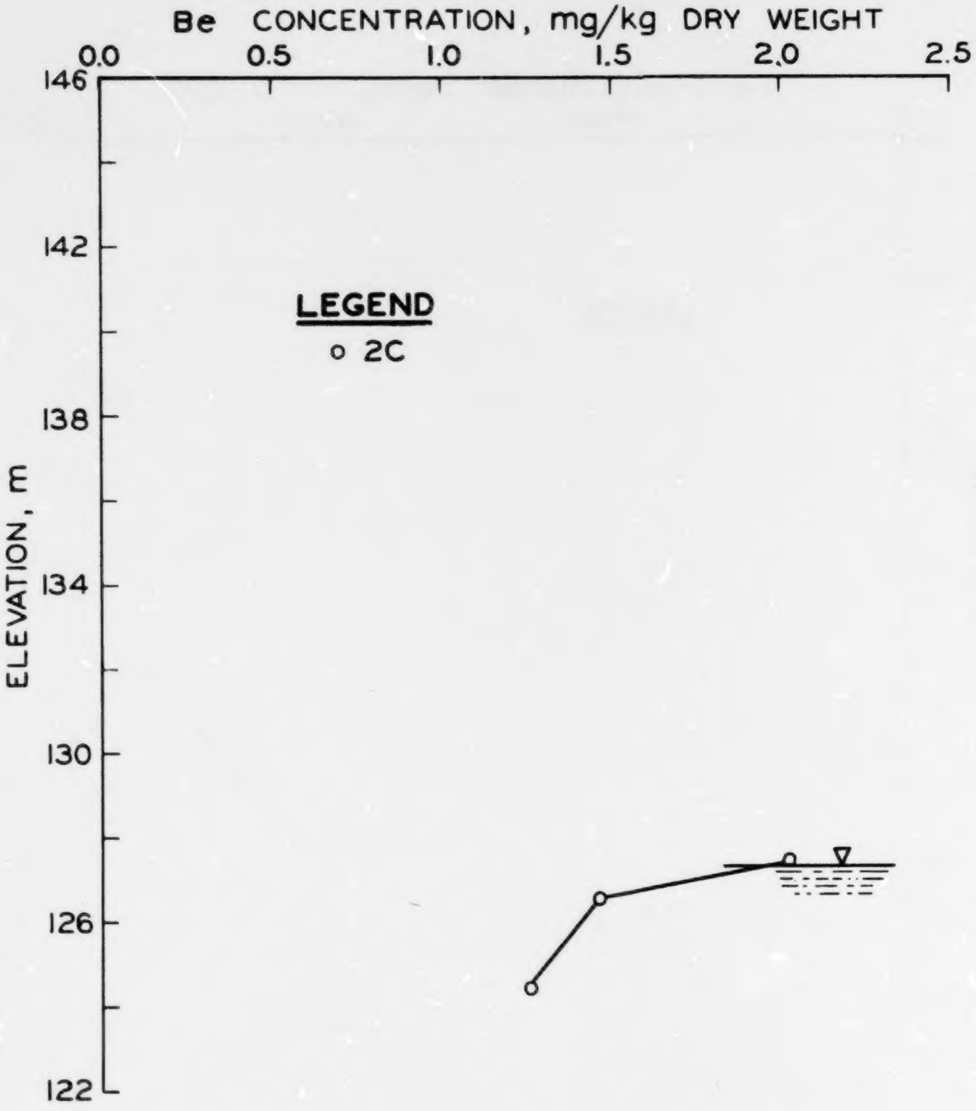


Figure 30. Variation of beryllium concentration in nitric acid digests of soil/sediment samples with elevation in boring 2 at site C. Inverted triangle symbol indicates water table.

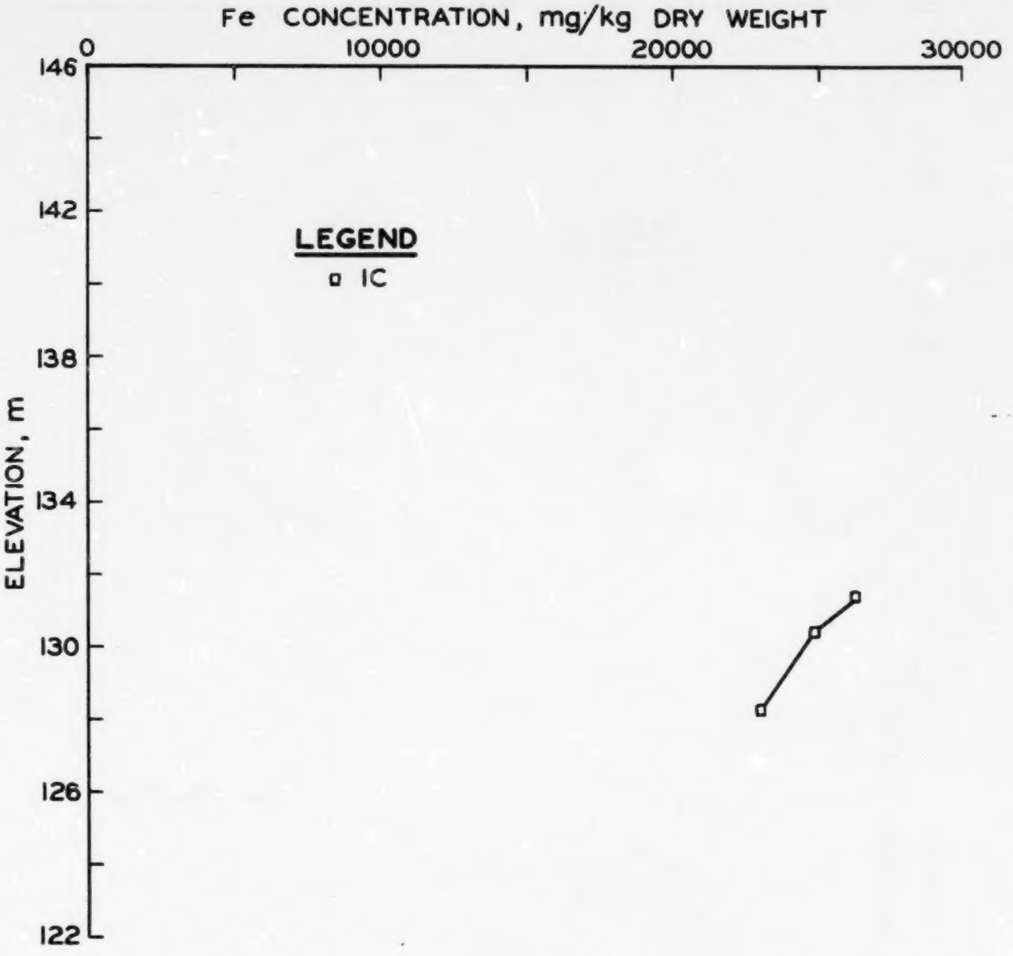


Figure 31. Variation of iron concentration in nitric acid digests of soil/sediment samples with elevation in boring 1 at site C.

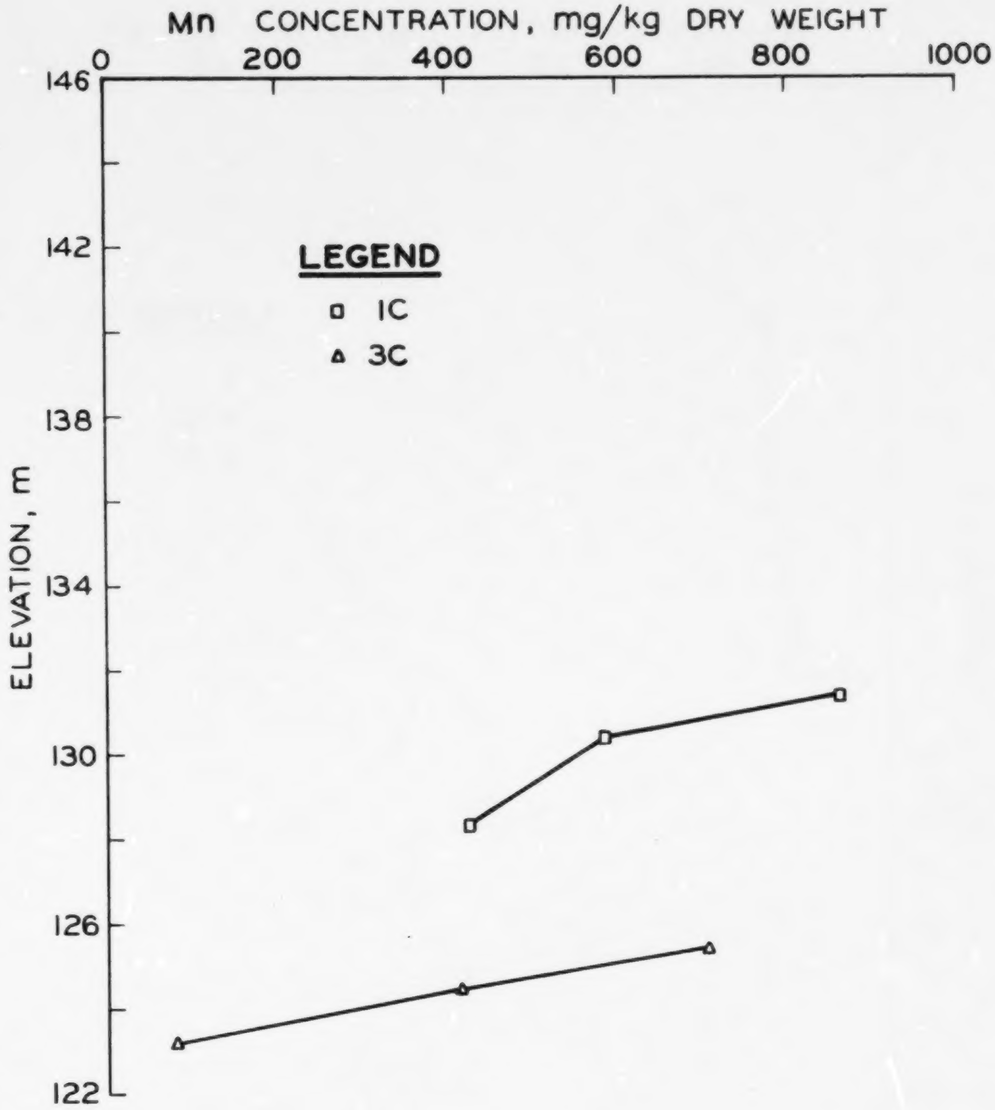


Figure 32. Variation in manganese concentration in nitric acid digests of soil/sediment samples with elevation in borings 1 and 3 at site C.

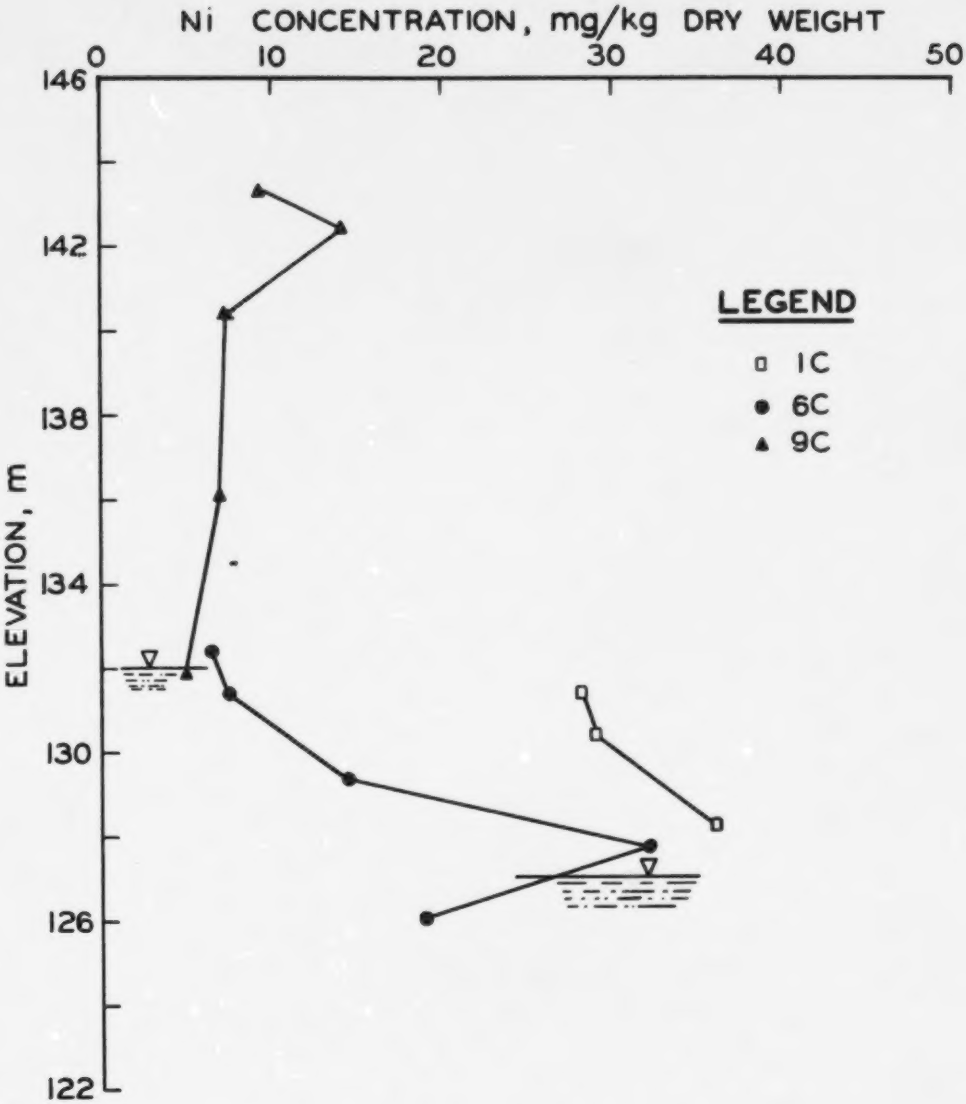


Figure 33. Variation of nickel concentration in nitric acid digests of soil/sediment samples with elevation in borings 1, 6 and 9 at site C. Inverted triangle symbols indicate water table in each boring.

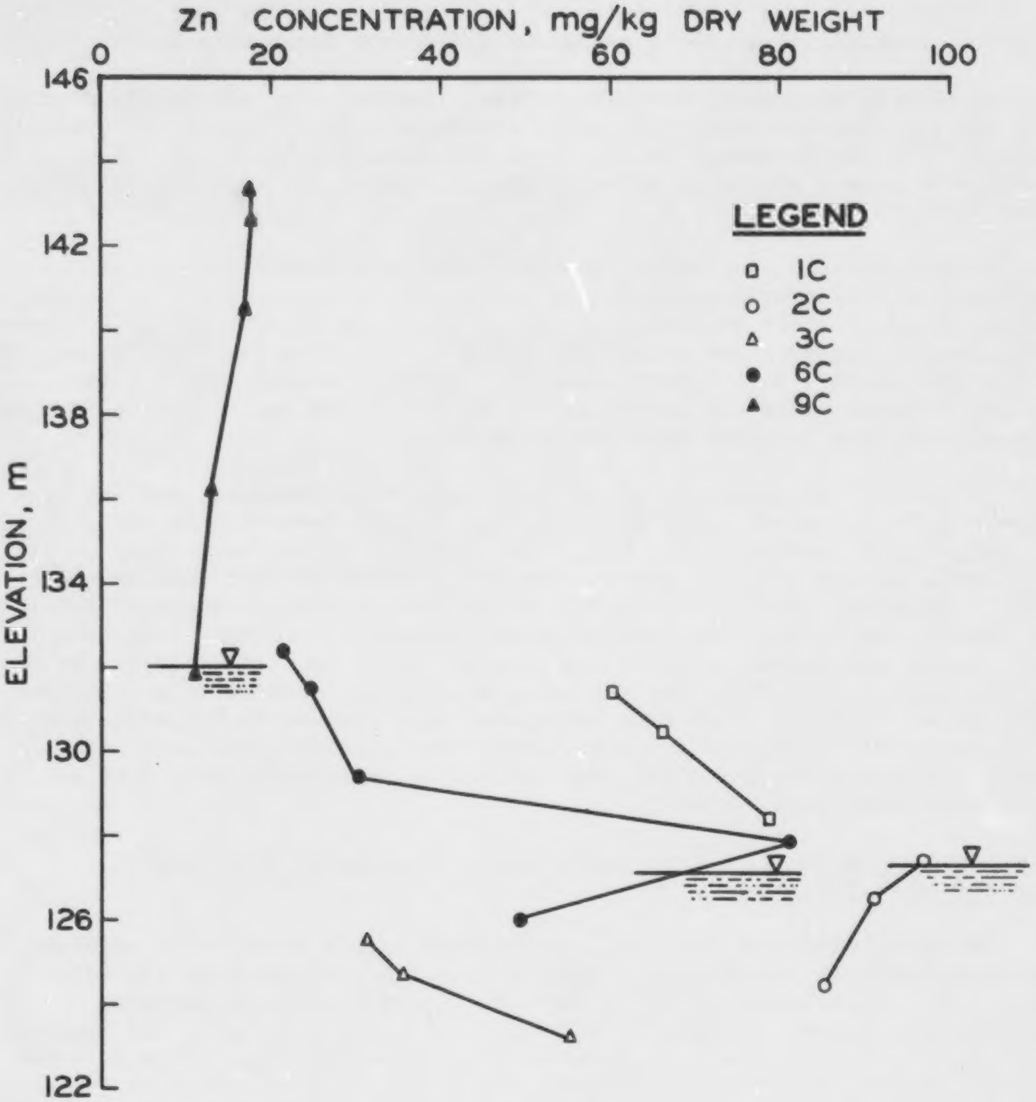


Figure 34. Variation of zinc concentration in nitric acid digests of soil/sediment samples with elevation in borings 1, 2, 3, 6 and 9 at site C. Inverted triangle symbols indicate water table in each boring.

At site A, boron and beryllium showed significant positive correlations with elevation. This correlation, together with their increased abundance under the fill suggests they are being added to the soil by landfill leachate. Selenium shows a positive correlation with elevation, but is not as abundant under the fill as outside the fill. This suggests selenium does leach down from the landfill but is being moved out and is not being held by the soil.

At site B, manganese, arsenic, copper, lead and zinc all showed significant positive correlations with sample elevation. The positive correlations together with the increased levels occurring under the landfill suggest that these constituents are being added to the soil under the landfill and are being retained.

At site C, iron, manganese, and beryllium showed significant positive correlations with sample elevation in borings below the landfill. The increased concentration of these metals under the landfill and the increasing concentrations upward suggest these metals are being leached from the landfill and held by the sub-landfill soil. Nickel and zinc showed a significantly larger concentration of metal under the landfill; but an increasing concentration downward suggests they are leaching from sub-refuse soil.

The ability of landfills to generate metal-rich leachates and the capacity of soils to retain these metals varies greatly from site to site. For the three sites studied, iron, manganese, arsenic, boron, beryllium, copper, lead, selenium and zinc all showed evidence of being derived from the landfills. Selenium, while it did appear to be most available immediately below the landfill at site A, was present in the samples in concentrations below that seen in surrounding soils of comparable depths indicating it was being leached from the landfill; but not being held by soil effectively. At site C, there is an indication that zinc and nickel were present in larger quantities under the landfill than in the area outside the landfill; but both metals showed increasing concentration with increasing depth suggesting they are being moved down into the soil.

Horizontal Variation in Nitric Acid Digests of Sediment/Soil Samples Near the Water Table

The model developed for leachate movement indicates that the major horizontal movement of contaminants from leachate takes place below the water table. If a contaminant is being added to the local soil or sediment by the landfill the highest concentrations should be in the soil below the landfill. Lower concentrations should be found in soil below the water table down the groundwater gradient from the landfill. This decrease in concentration is related to the filtration, absorption or precipitation occurring in the soil or sediment as the groundwater flow moves the leachate away from the landfill. Samples of geologic materials (sediments or soils) were digested to determine if any pattern of contaminant concentration could be related to the direction of movement of groundwater.

At site A, the samples collected near the water table in borings 6 and 7 (downgradient) are from a sandstone unit below the glacial valley-fill material thus some influence of the changing nature of the sediment may be expected in these acid digests. At site C, one sample taken upgradient (boring 4) and one sample taken downgradient (boring 7) were taken from the surface of the underlying schist. Digests from this less-weathered metamorphic rock would be expected to differ considerable from that of the soil produced by the weathering of the rock. At these two sites some reservations must be taken with regard to interpreting the variation in chemistry as due solely to the influence of the landfill.

The small number of samples precluded use of statistical comparison techniques. Graphs showing the concentration of various metals versus the relative positions of the borings with respect to the landfill are given in Figures 35-37.

At site A, maximum concentrations of manganese, boron, cadmium, chromium, copper, nickel, lead, selenium and zinc occurred in samples taken under the landfill. Samples taken at or near the water table downdip showed decreasing amounts of these constituents. Arsenic is the only contaminant that showed a maximum concentration in a downdip boring.

At site B, iron, arsenic, beryllium, cadmium, mercury, selenium and zinc all reached maximum concentrations in samples collected under the landfill. Manganese, boron, chromium, copper, nickel and lead all reach maximum concentrations in borings downdip from the landfill.

At site C, iron, boron, cadmium, nickel, selenium, and zinc all reached maximum concentrations in samples collected under the landfill. Manganese, arsenic, copper, mercury and lead all reached maximum concentrations in samples collected downdip from the landfill. Beryllium and chromium were found in their greatest concentrations in samples taken updip from the landfill.

A pattern can be observed in the location of concentration maxima. At all three sites the maximum concentration of arsenic is displayed downdip. At two sites (B and C) maximum concentrations for manganese, copper and lead were found in downdip borings.

DISCUSSION

Physical testing showed no consistent attribute in the soil/sediment samples collected at the landfill sites that could be related to the presence of the landfilled refuse. There was no detectable change in density, permeability, grain size distribution or water content that could be shown to be a response to the movement of leachate. Griffin and others (15) showed that changes in permeability could be observed in experimental columns filled with clay and then subjected to landfill leachate. Permeability changes that occurred probably involved a relatively small volume of the soil at the very top of the soil column. However, in this investigation, field conditions did not always permit recovery of the sample which included only the interface between the refuse and soil/sediment.

Extending the model, the chemical behavior of contaminants in soil under ideal conditions can be broken into three basic types of interactions: flow through, attenuation and mobilization. Flow through is essentially that [illegible]

Reproduced from best available copy.

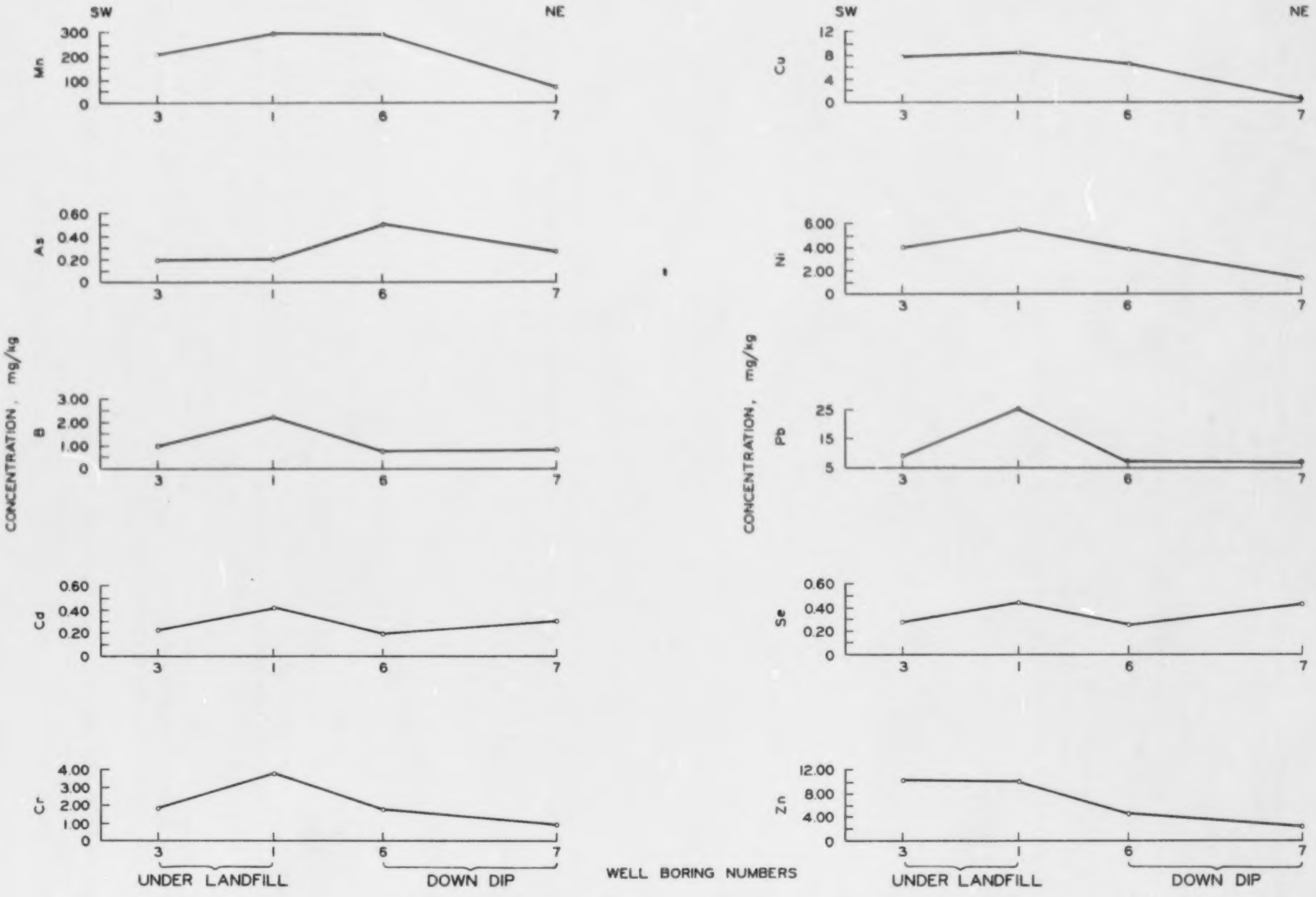


Figure 35. Horizontal variation in chemical composition of nitric acid digests at site A.

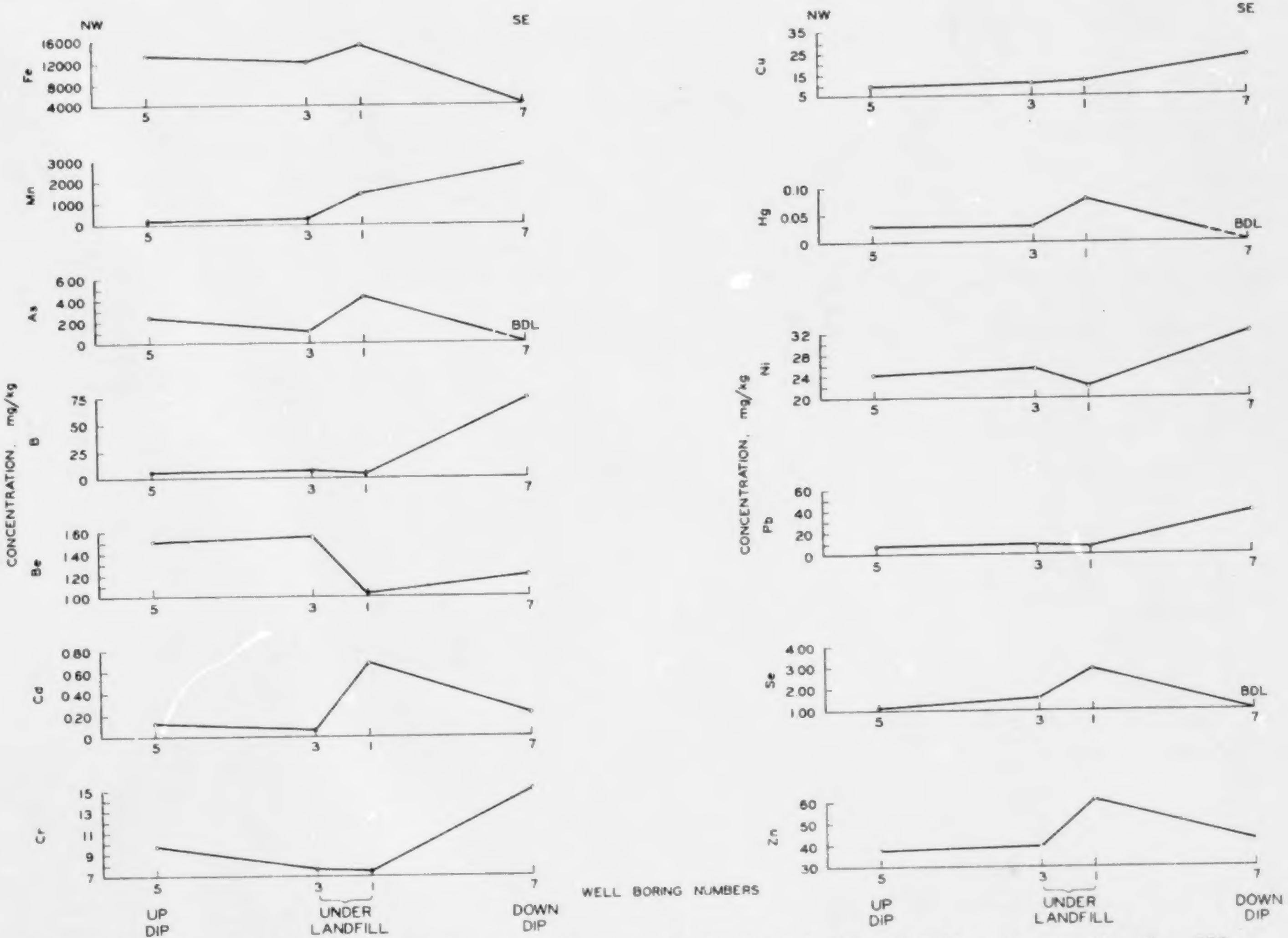


Figure 36. Horizontal variation in chemical composition of nitric acid digests at site B. BDL indicates below detection limits.

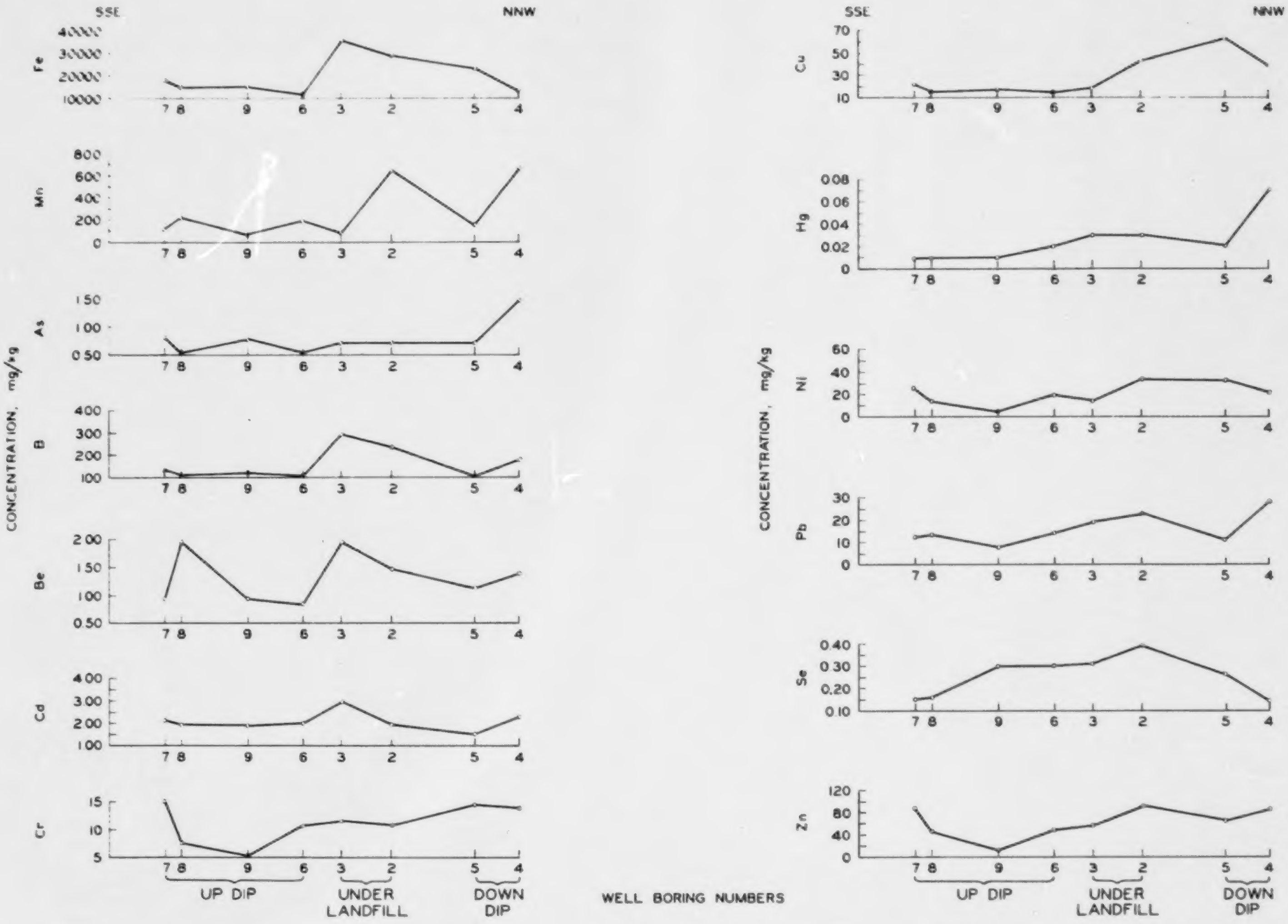


Figure 37. Horizontal variation in chemical composition of nitric acid digests at site C.

where negligible chemical interaction takes place. The porous matrix (soil) is inert and does not effectively filter, absorb or precipitate the contaminants. Therefore, no changes can be detected in the composition of the soil. Cases in which the difference in concentration of contaminants in the nitric acid digests of the soil samples varied less than 25% between samples inside the landfill and outside were judged to be examples of "flow through". The instances of "flow through" are indicated in Table 35 (samples marked "X" in nitric acid digest column). At all three sites cadmium and chromium had essentially the same concentrations in the nitric acid digests of soil inside and outside the landfill. Similarly, nickel (sites A and B), boron (sites B and C), selenium (sites A and B), beryllium (site B), copper (site A), manganese (site A) and mercury (site A) were found in equal concentrations. In most of these cases, the metals are also found in higher concentrations in groundwater collected under the refuse as would be expected. Earlier investigations (15) have indicated that attenuation should be effective in removing toxic metals, the analyses of soil digests given here do not demonstrate a trapping mechanism for most contaminants.

A second type of interaction takes place when the soil removes contaminants by filtration, absorption and/or precipitation. The ability of soil to attenuate contaminants in this manner is limited by the capacity of the soil to contain pollutants. Up to the time when the capacity is reached, the amount of contaminant in the soil increases while the amount passing through to the groundwater is lessened (Table 35). Therefore, the nitric acid digest analyses should show higher levels of contaminants under the refuse and the concentrations in groundwater under and outside the landfill should be nearly equal. After the capacity of the soil for attenuating the contaminant has been reached, concentrations of these contaminants in the groundwater should increase.

Examples of attenuation where soil capacity has not been reached and groundwater concentrations have not increased are beryllium (sites A and C), arsenic (site A), copper (site B) and mercury (site C). Examples of cases where the capacity of the soil to attenuate the contaminant has been reached or exceeded (concentrations in the groundwater have increased under the refuse) are zinc (all three sites), iron and manganese (sites B and C), lead (sites A and C), arsenic (site B), boron (site A) and nickel (site C).

The third possible interaction is the mobilization of soil constituents by the acids typically occurring in the leachate from the refuse. This action brings materials into solution that would normally remain fixed in the soil and brings about a lower concentration of the material in the nitric acid digests of the soil samples from under the landfill when compared with those outside the landfill (Table 35). Only arsenic at site C showed a distribution pattern in the nitric acid digest and the groundwater that would indicate mobilization is occurring.

In some of the samples where attenuation was indicated, this trend was further substantiated by the decreased extractability (into distilled water) observed in samples collected underneath the landfill. While this decreased extractability was not observed in all cases, it might be a useful indicator of the formation of highly insoluble phases during attenuation.

Reproduced from
best available copy.

TABLE 35. COMPARISON OF AVERAGE CHEMICAL COMPOSITION OF GROUNDWATER AND SOIL SAMPLES FROM EXPERIMENTAL AND CONTROL BORINGS FOR ALL SITES

Chemical constituents	Groundwater	Site A distilled* water extract	HNO_3* digest	Groundwater	Site B distilled water extract	HNO_3 digest	Groundwater	Site C distilled water extract	HNO_3 digest
SO_4	+	X	ND	+	BDL	ND	+	-	ND
SO_3	BDL	BDL	ND	+	BDL	ND	BDL	BDL	ND
Cl	+	BDL	ND	+	BDL	ND	+	+	ND
NO_3-N	+	+	ND	-	-	ND	-	-	ND
NO_2-N	+	BDL	ND	BDL	BDL	ND	BDL	BDL	ND
CN	+	BDL	ND	+	+	ND	+	BDL	ND
TOC	+	+	ND	+	+	ND	+	+	ND
Ca	+	X	ND	+	+	ND	+	-	ND
Fe	+	ND	ND	+	+	+	+	-	+
Mg	+	+	ND	+	X	ND	+	X	ND
Mn	+	BDL	X	+	+	+	+	-	+
Na	+	+	ND	+	+	ND	+	+	ND
As	X	+	+	+	ND	+	+	ND	-
B	+	BDL	+	X	+	X	+	+	X
Be	-	BDL	+	+	BDL	X	X	BDL	+
Cd	+	BDL	X	X	BDL	X	+	BDL	X
Cr	-	+	X	X	+	X	BDL	BDL	X
Cu	X	+	X	X	BDL	+	BDL	BDL	+
Hg	BDL	ND	BDL	-	ND	X	-	ND	+
Ni	+	+	X	+	-	X	+	-	+
Pb	+	BDL	+	BDL	BDL	+	+	ND	+
Se	BDL	BDL	X	+	ND	X	BDL	ND	+
Zn	+	+	+	+	BDL	+	+	-	+

+ = >125% of average control sample.

X = 75% to 125% of average control sample.

- = <75% of average control sample.

BDL = More than one half samples below detection limits.

ND = Not determined.

* Note that soil samples used in averages were those at the interface between refuse and subsoil, and comparable levels outside the landfill.

If the number of metals found in greater abundance in the nitric acid digest from samples taken directly under the landfill is used as an index of overall attenuation; site C shows the most active attenuation. Site B and site A rank second and third respectively, although they are nearly identical.

The character of the soil/sediment in the area of attenuation and the chemical activity within the refuse leachate appear to be of prime importance in the attenuation process. In the present study, the poorest attenuation was associated with an older site having coarse sandy material under the landfill. The most effective attenuation appears in a landfill that is relatively young and underlain by fine-grained material. The high rate of microbial activity associated with this younger landfill should produce a large quantity of hydrogen sulfide in the leachate and precipitate the chalcophile elements (i.e., those having an affinity for sulfur) such as iron, nickel, copper, zinc, mercury and lead.

REFERENCES

1. Schneider, W. J. Hydrologic Implications of Solid-Waste Disposal. Circ. 601-F, U. S. Geol. Surv., Washington D. C., 1970. 10 pp.

2. Garland, G. A. and D. C. Mosher. Leachate Effects of Improper Land Disposal. Waste Age, March 1975. pp. 42-48.

3. Exler, H. J. Defining the Spread of Groundwater Contamination Below a Waste Tip. In: Ground Water Pollution in Europe, J. A. Cole, ed. Water Information Center, Port Washington, New York, 1974. pp. 215-241.

4. Hughes, G. M., R. A. Landon, and R. N. Farvolden. Hydrogeology of Solid Wastes Disposal Sites in Northeastern Illinois. Solid Waste Report SW-12d, U. S. Environmental Protection Agency, Washington, D. C., 1971. 154 pp.

5. Qasim, S. R. and J. C. Burchinal. Leaching from Simulated Landfills. J. Water Pollution Control Fed. 42 (3, pt. 1): 371-379, 1970.

6. U. S. Army Engineer, Waterways Experiment Station. The Unified Soil Classification System. Tech. Memorandum No. 3-257, Vol. 1, USAE Waterways Experiment Station, Vicksburg, Mississippi, 1960. 30 pp.

7. Levinson, A. A. Introduction to Exploration Geochemistry. Applied Publ. Co. Ltd. Calgory, Canada, 1974. 612 pp.

8. Ward, F. N., H. M. Nakagawa, T. F. Harms, and G. H. VanSickle. Atomic Absorption Methods of Analysis Useful in Geochemical Exploration. Bull. 1289, U. S. Geol. Surv., Washington, D. C., 1969. 45 pp.

9. Foster, J. R. The Reduction of Matrix Effects in Atomic Absorption Analysis and the Efficiency of Selected Extractions on Rock Forming Minerals. In: Geochemical Exploration, The Canadian Institute of Mining and Metallurgy. Special Vol. 11, Ottawa, Canada, 1971. pp. 554-560.

10. U. S. Dept. of the Army. Laboratory Soils Testing Engineering Manual EM 1110-2-1906, U. S. Dept. of the Army, Washington, D. C., 1970. No pagination.

11. U. S. Environmental Protection Agency. Manual of Methods of Chemical Analyses of Water and Wastes. EPA 625/6-74-003, U. S. Environmental Protection Agency, Cincinnati, Ohio, 1971. 298 pp.

12. Siegel, Sidney. Nonparameteric Statistics for the Behavioral Sciences. McGraw-Hill Book Co., New York, 1956. 312 pp.

13. Siddiqui, and R. R. Parizek. Application of Nonparametric Statistical Tests in Hydrogeology. Groundwater, 10(2):26-31, 1972.

14. Palmquist, R. and L. V. A. Sendlein. The Configuration of Contaminated Enclaves from Refuse Disposal Sites on Floodplains. Groundwater, 13(2): 167-181, 1975.

15. Griffin, R. A. and others. Attenuation of Pollutants in Landfill Leachate by Clay Minerals. Environmental Geology Notes No. 78, Illinois Geological Survey, Urbana, Illinois, 1976. 34 pp.

APPENDIX A

SUB-SURFACE INFORMATION FOR SITE A

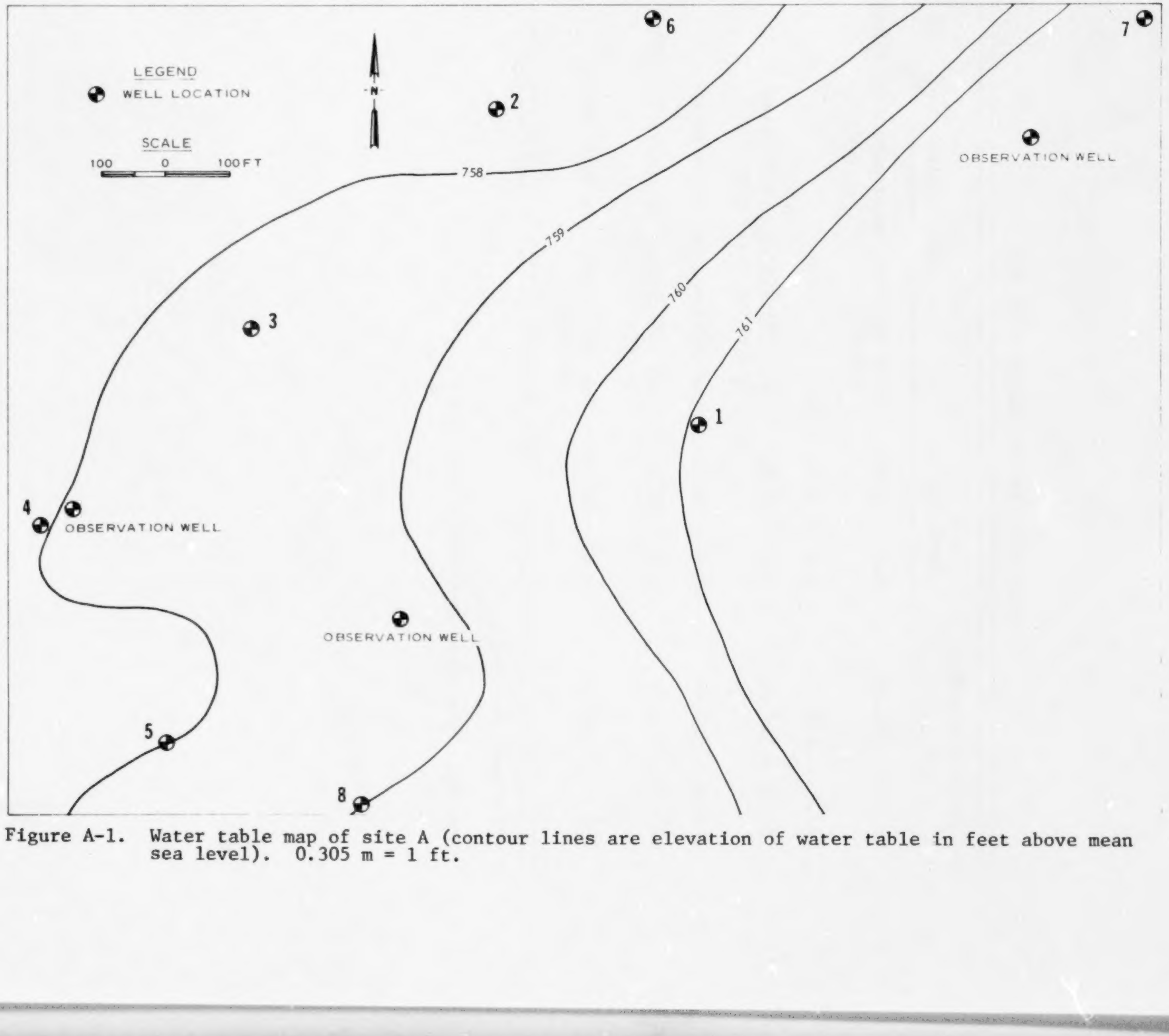

LEGEND
WELL LOCATION
SCALE
100
0
100 FT
N
758
759
760
761
1
2
3
4
5
6
7
8
OBSERVATION WELL
OBSERVATION WELL
OBSERVATION WELL

Figure A-1. Water table map of site A (contour lines are elevation of water table in feet above mean sea level). 0.305 m = 1 ft.

TABLE A-1. LOG OF BORING 1 AT SITE A

Elevation above MSL* (m)	Depth (m)	Description
257.96 - 257.29	0.0 - 0.67	Cover material (sand with some large gravel)
257.29 - 250.76	0.67 - 7.20	Fill
250.76 - 247.08	7.20 - 10.88	Sand (SP) medium, light brown with traces of small gravel
247.08 - 235.58	10.88 - 22.38	Sand (SP) medium, light brown
235.58 - 232.53	22.38 - 25.43	Sand (SP) medium to coarse tan with scattered gravel
232.53 - 229.88	25.43 - 28.08	Sand (SP) fine, tan with orange streaks

* MSL = mean sea level

Water table elevation above MSL = 232.53 m

TABLE A-2. LOG OF BORING 2 AT SITE A

Elevation above MSL* (m)	Depth (m)	Description
257.00 - 255.78	0.0 - 1.22	Cover material (sand (SP)) medium to coarse, some gravel
255.78 - 251.24	1.22 - 5.76	Waste
251.24 - 250.32	5.76 - 6.68	Sand (SP) medium, light brown
250.32 - 247.58	6.68 - 9.42	Sand (SP) medium to coarse, light brown with gravel
247.58 - 230.5	9.42 - 26.50	Sand (SP) medium to coarse light brown with gravel

Water table elevation above MSL = 231.01 m

TABLE A-3. LOG OF BORING 3 AT SITE A

Elevation above MSL (m)	Depth (m)	Description
258.57 - 255.52	0.0 - 3.05	Cover material (sand (SP)) medium to coarse brown
255.52 - 250.71	3.05 - 7.86	Fill
250.71 - 236.31	7.86 - 22.26	Sand (SP), medium to coarse, brown with gravel
236.31 - 229.97	22.26 - 28.60	Gravely sand (SP) medium to coarse, brown

Water table elevation above MSL = 231.22 m

TABLE A-4. LOG OF BORING 4 AT SITE A

Elevation above MSL (m)	Depth (m)	Description
253.60 - 249.49	0.0 - 4.11	Sand (SP) medium to coarse, light brown
249.49 - 247.35	4.11 - 6.25	Sand (SP) medium, brown with some gravel
247.35 - 242.78	6.25 - 10.82	Sand (SP) fine to medium, light brown
242.78 - 241.80	10.82 - 11.80	Sandy gravel (GP), light brown
241.80 - 236.99	11.80 - 16.61	Sand (SP) medium to coarse, light brown with some gravel
236.99 - 236.38	16.61 - 17.22	Sandy gravel (GP), light brown
236.38 - 230.12	17.22 - 23.48	Gravelly sand (SP), medium to coarse

Water table elevation above MSL = 230.91 m

TABLE A-5. LOG OF BORING 5 AT SITE A

Elevation above MSL (m)	Depth (m)	Description
255.02 - 241.91	0.0 - 13.11	Sand (SP), medium to coarse, light brown with gravel
241.91 - 237.18	13.11 - 17.84	Sand (SP), medium to coarse, light brown
237.18 - 236.57	17.84 - 18.45	Gravelly sand (SP), brown
236.57 - 236.06	18.45 - 18.96	Sand (SP), medium to coarse, light brown
236.06 - 231.24	18.96 - 23.78	Sand (SP), medium to coarse, light brown with gravel
231.24 - 230.23	23.78 - 24.79	Sand (SP), medium to coarse, brown

Water table elevation above MSL = 231.10 m

TABLE A-6. LOG OF BORING 6 AT SITE A

Elevation above MSL (m)	Depth (m)	Description
256.01 - 255.77	0.0 - 0.24	Sand (SP) fine-medium, dark brown
255.77 - 254.33	0.24 - 1.68	Sand (SP), fine-medium, brown
254.33 - 242.23	1.68 - 13.78	Sand (SP) medium-coarse, brown with gravel
242.23 - 232.08	13.78 - 23.93	Sand (SP), medium-coarse, light brown scattered small gravel
232.08 - 231.47	23.43 - 24.54	Gravelly sand (SP), brown
231.47 - 231.16	24.54 - 24.85	Sand (SP), medium-coarse, light brown, with gravel
231.16 - 231.10	24.85 - 24.91	Sandstone, tan
231.10 - 229.95	24.91 - 26.06	Sand (SP), medium, brown

Water table elevation above MSL = 231.10 m

TABLE A-7. LOG OF BORING 7 AT SITE A

Elevation above MSL (m)	Depth (m)	Description
255.64 - 254.73	0.0 - 0.91	Sand (SP), fine-medium, dark brown
254.73 - 252.60	0.91 - 3.04	Sand (SP), fine-medium, brown
252.60 - 250.82	3.04 - 4.82	Sand (SP), coarse, light brown with gravel
250.82 - 250.30	4.82 - 5.34	Sand (SP), medium-coarse, light brown
250.30 - 247.16	5.34 - 8.48	Gravelly sand (SP), medium-coarse, brown
247.16 - 240.40	8.48 - 15.24	Sand (SP), medium-coarse, brown with gravel
240.40 - 238.87	15.24 - 16.77	Sandy gravel (GP), brown
238.87 - 237.20	16.77 - 18.44	Sand (SP), medium-coarse, light brown with gravel
237.20 - 235.52	18.44 - 20.12	Sandstone, tan
235.52 - 233.08	20.12 - 22.56	Sand, fine-medium, light brown

Water table elevation above MSL = 235.52 m

TABLE A-8. LOG OF BORING 8 AT SITE A

Elevation above MSL (m)	Depth (m)	Description
265.04 - 264.28	0.0 - 0.76	Sand (SP), fine, dark brown
264.28 - 264.13	0.76 - 0.91	Sand (SP), medium, brown with gravel
264.13 - 258.94	0.91 - 6.10	Sand (SP), coarse, brown with gravel
258.94 - 249.10	6.10 - 15.94	Sand (SP), medium-coarse, brown, trace of gravel
249.10 - 242.18	15.94 - 22.86	Sand (SP), medium-coarse, brown, with gravel
242.18 - 241.72	22.86 - 23.32	Sandy gravel (GP), brown
241.72 - 231.35	23.32 - 33.69	Sand (SP), medium-coarse, brown with gravel
231.35 - 230.34	33.69 - 34.7	Sand (SP), medium-coarse, light brown

Water table elevation above MSL = 235.52 m

TABLE A-9. LIST OF SAMPLES EXAMINED FROM SITE A

Boring	Elevation of top of hole (m)	Elevation of water table (m)	Total depth (m)	Thickness of cover (m)	Thickness of refuse (m)	Elevation MW/soil interface (m)	Sampled depth interval(m)		Elevation of sampled intervals(m)		Type of sample	Sample number
							From	To	From	To		
1	257.96	232.53	28.26	0.67	6.52	250.77	7.20	7.70	250.76	250.26	physical	1C1
							7.37		250.59		chemical	1C2
							8.19		249.77		chemical	1C3
							10.38		247.58		chemical	1C4
							10.94	11.64	247.02	246.32	physical	1P1
							15.88		242.08		chemical	1C5
							22.65	22.84	235.31	235.12	physical	1P2
							23.15		234.81		chemical	1C6
							27.13		230.83		chemical	1C7
							27.13		230.83		chemical	1C8
2	257.01	231.01	29.52	1.22	4.85	250.94	6.03		250.98		chemical	2C1
							6.25	6.68	250.76	250.33	physical	2P1
							6.87		250.14		chemical	2C2
							6.92	7.44	250.09	249.57	physical	2P2
							8.81	9.42	248.20	249.59	physical	2P3
							9.02		247.99		chemical	2C3
							13.87	14.39	243.14	242.62	physical	2P4
							14.01		243.00		chemical	2C4
							19.51	19.87	237.50	237.14	physical	2P5
							19.90		237.11		chemical	2C5
							24.39	24.94	232.62	232.07	physical	2P6
							24.93		232.08		chemical	2C6
3	258.57	231.22	31.80	3.05	4.82	250.70	7.86	8.32	250.71	250.25	physical	3P1
							8.04		250.53		chemical	3C1
							9.04		249.53		chemical	3C2

(continued)

TABLE A-9. (continued)

Boring	Elevation of top of hole (m)	Elevation of water table (m)	Total depth (m)	Thickness of cover (m)	Thickness of refuse (m)	Elevation MW/soil interface (m)	Sampled depth interval(m) From	Sampled depth interval(m) To	Elevation of sampled intervals(m) From	Elevation of sampled intervals(m) To	Type of sample	Sample number
							10.82	11.25	247.75	247.32	physical	3P2
							17.97		240.60		chemical	3C3
							18.30		240.27		chemical	3C4
							22.25	22.53	236.32	236.04	physical	3P3
							22.85		235.72		chemical	3C5
							27.84		230.73		chemical	3C6
4	253.60	230.91	23.48	NA	NA	NA	3.20	3.90	250.4	249.7	physical	4P1
							6.25	6.62	247.35	246.98	physical	4P2
5	257.15	231.10	24.79	NA	NA	NA	4.57	5.29	252.58	251.86	physical	5P1
							7.62	8.20	249.53	248.95	physical	5P2
							18.44	18.83	238.71	238.32	physical	5P3
6	256.01	231.10	26.06	NA	NA	NA	4.72	5.33	251.29	250.69	physica	6P1
							4.92		251.09		chemical	6C1
							5.81		250.20		chemical	6C2
							7.77	8.42	248.24	247.59	physical	6P2
							7.93		248.08		chemical	6C3
							13.96		242.05		chemical	6C4
							19.00	19.48	237.01	236.53	physical	6P3
							19.15		236.86		chemical	6C5
							25.17		230.84		chemical	6C6
7	255.64	235.52	22.56	NA	NA	NA	4.42	4.76	251.22	250.88	physical	7P1
							5.15		250.44		chemical	7C1
							5.49		250.15		chemical	7C2
							7.65		247.99		chemical	7C3
							7.77	8.26	247.87	247.38	physical	7P2
							13.26	13.75	242.38	241.89	physical	7P3

(continued)

TABLE A-9. (concluded)

Boring	Elevation of top of hole (m)	Elevation of water table (m)	Total depth (m)	Thickness of cover (m)	Thickness of refuse (m)	Elevation MW/soil interface (m)	Sampled depth interval(m) From	Sampled depth interval(m) To	Elevation of sampled intervals(m) From	Elevation of sampled intervals(m) To	Type of sample	Sample number
							13.41		242.23		chemical	7C4
							19.27		236.37		chemical	7C5
							22.32		233.32		chemical	7C6
8	265.04	231.37	34.70	NA	NA	NA	14.32	15.03	250.72	250.01	physical	8P1
							17.38	17.96	247.66	247.08	physical	8P2
							28.65	28.99	236.39	236.05	physical	8P3

NA = not applicable

APPENDIX B

SUB-SURFACE INFORMATION FOR SITE B

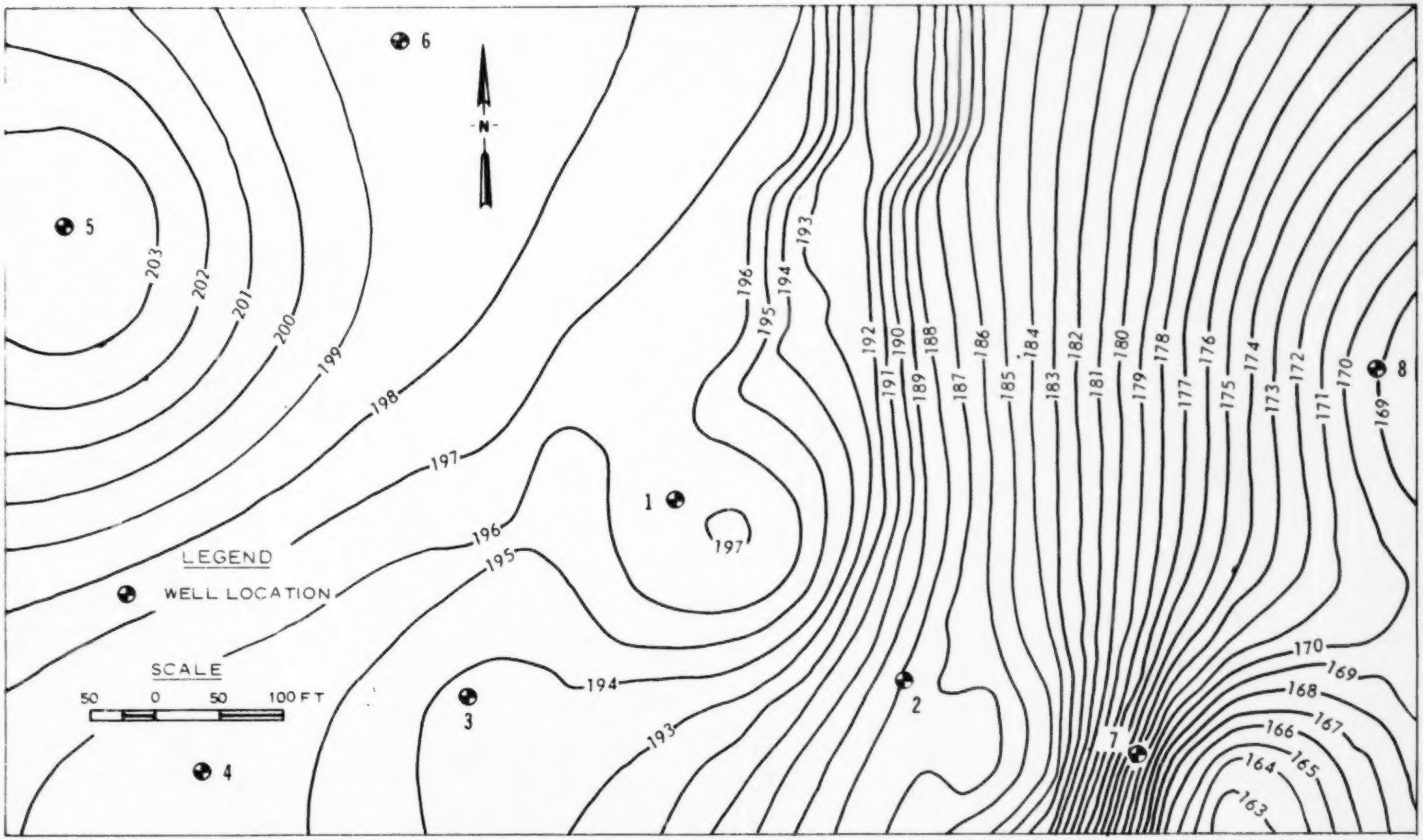

5
6
N
203
202
201
200
199
198
197
196
195
194
193
LEGEND
WELL LOCATION
SCALE
50
0
50
100 FT
4
3
1
197
196
195
194
193
192
191
190
189
188
187
186
185
184
183
182
181
180
179
178
177
176
175
174
173
172
171
170
169
8
2
7
170
169
168
167
166
165
164
163

Figure B-1. Water table map of site B (contour lines are elevation of water table in feet above mean sea level). 0.305 m = 1 ft.

TABLE B-1. LOG OF BORING 1 AT SITE B

Elevation above MSL(m)	Depth (m)	Description
60.15 - 54.27	0.0 - 5.88	Refuse
54.27 - 51.74	5.88 - 8.41	Clayey silt (ML), gray
51.74 - 51.03	8.41 - 9.12	Silty clay (CL), gray

Water table elevation above MSL = 54.34 m

TABLE B-2. LOG OF BORING 2 AT SITE B

Elevation above MSL(m)	Depth (m)	Description
57.20 - 57.9	0.0 - 0.30	Backfill
57.90 - 54.46	0.30 - 2.74	Refuse
54.46 - 51.41	2.74 - 5.79	Clayey silt (ML), gray
51.41 - 48.05	5.79 - 9.15	Clayey silt (ML), tan

Water table elevation above MSL = 50.94 m

TABLE B-3. LOG OF BORING 3 AT SITE B

Elevation above MSL (m)	Depth (m)	Description
58.96 - 58.66	0.0 - 0.30	Topsoil
58.66 - 56.74	0.30 - 2.22	Refuse
56.74 - 56.22	2.22 - 2.74	Silt (ML), gray
56.22 - 52.86	2.74 - 6.10	Silt (ML), tan, wet

Water table elevation above MSL = 53.23 m

TABLE B-4. LOG OF BORING 4 AT SITE B

Elevation above MSL (m)	Depth (m)	Description
59.51 - 55.24	0.0 - 4.27	Silt (ML), tan
55.24 - 51.89	4.27 - 7.62	Silt (ML), tan and grayish tan, wet

Water table elevation above MSL = 53.84 m

TABLE B-5. LOG OF BORING 5 AT SITE B

Elevation above MSL (m)	Depth (m)	Description
62.20 - 57.63	0.0 - 4.57	Silt (ML), tan
57.63 - 54.58	4.57 - 7.62	Silt (ML), tan, wet
54.58 - 52.44	7.62 - 9.76	Silt (ML), tan with gray specks, wet

Water table elevation above MSL = 53.35 m

TABLE B-6. LOG OF BORING 6 AT SITE B

Elevation above MSL (m)	Depth (m)	Description
60.52 - 54.42	0.0 - 6.10	Silt (ML), tan
54.42 - 51.37	6.10 - 9.15	Silt (ML), tan and gray
51.37 - 49.54	9.15 - 10.98	Silt (ML), tan with shells

Water table elevation above MSL = 50.15 m

TABLE B-7. LOG OF BORING 7 AT SITE B

Elevation above MSL (m)	Depth (m)	Description
49.42 - 48.81	0.0 - 0.61	Refuse
48.81 - 45.91	0.61 - 3.51	Silt (ML), gray
45.91 - 41.80	3.51 - 7.62	Silt (ML) tan, moist

Water table elevation above MSL = 42.10 m

TABLE B-8. LOG OF BORING 8 AT SITE B

Elevation above MSL (m)	Depth (m)	Description
50.91 - 46.34	0.0 - 4.57	Silt (ML)
46.34 - 43.29	4.57 - 7.62	Silt (ML), gray, wet
43.29 - 43.08	7.62 - 7.83	Silt (ML), tan
43.08 - 42.65	7.83 - 8.26	Silt (ML), light gray with shells

Water table elevation above MSL = 45.61 m

TABLE B-9. LIST OF SAMPLES EXAMINED FROM SITE B

Boring	Elevation of top of hole (m)	Elevation of water table (m)	Total depth (m)	Thickness of cover (m)	Thickness of refuse (m)	Elevation MW*/soil interface (m)	Sampled depth interval(m)		Elevation of sampled intervals(m)		Type of sample	Sample number
							From	To	From	To		
1	60.15	54.36	9.14	0.0	4.88	55.27	4.22		55.93		chemical	1C1
							6.09		54.06		chemical	1C2
							6.25	6.37	53.90	53.78	physical	1P1
							8.41	8.87	51.74	51.28	physical	1P2
2	57.20	50.94	9.14	0.3	2.44	54.46	0.43		56.77		chemical	2C1
							1.35		55.85		chemical	2C2
							3.48		53.72		chemical	2C3
							3.66	4.15	53.54	53.05	physical	2P1
							5.79	6.52	51.41	50.68	physical	2P2
3	58.96	53.23	6.10	0.3	1.92	56.74	2.22		56.74		chemical	3C1
							3.22		55.74		chemical	3C2
							5.46		53.50		chemical	3C3
4	59.51	53.84	7.62	NA	NA	NA**	—		—		—	--
5	62.20	53.35	9.76	NA	NA	NA	0.20		55.28		chemical	5C1
							0.92		54.38		chemical	5C2
							3.05		52.44		chemical	5C3
6	60.52	50.15	10.98	NA	NA	NA	5.9		54.26		chemical	6C1
							6.10	6.77	54.42	53.75	physical	6P1
							7.17		53.35		chemical	6C2
							9.15	9.85	51.37	50.67	physical	6P2
							9.30		51.22		chemical	6C3
7	49.42	42.10	7.62	0.0	0.61	0.61	4.57	5.27	44.85	44.15	physical	7P1
							7.42		42.00		chemical	7C1
8	50.91	45.61	8.26	NA	NA	NA	6.10	6.68	44.81	44.23	physical	8P1

* municipal waste
** not applicable
-- no sample selected

APPENDIX C

SUB-SURFACE INFORMATION FOR SITE C

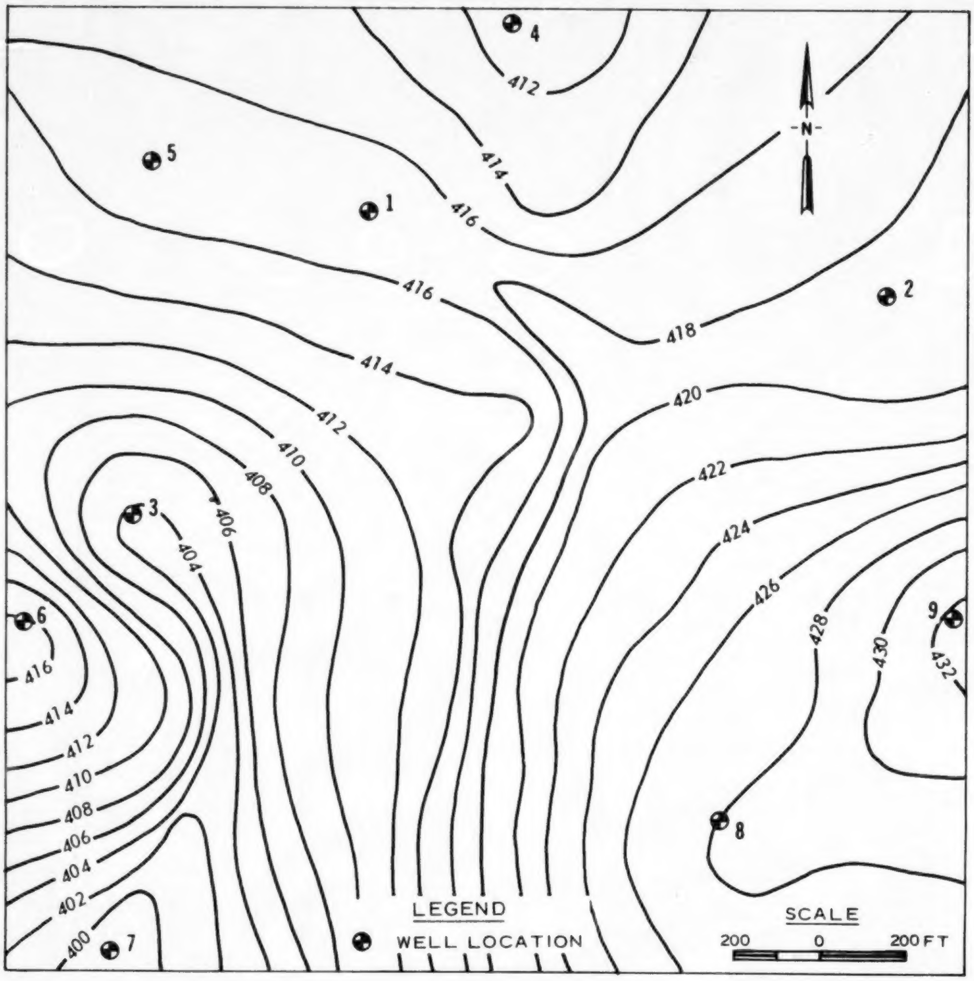

4
412
-N-
5
414
1
416
416
2
418
414
420
412
410
408
422
3
406
404
424
426
6
9
428
430
432
416
414
412
410
408
406
404
402
8
400
7
LEGEND
WELL LOCATION
SCALE
200
0
200 FT

Figure C-1. Water table map of site C (contour lines are elevation of water table in feet above mean sea level). 0.305 m = 1 ft.

TABLE C-1. LOG OF BORING 1 AT SITE C

Elevation above MSL* (m)	Depth (m)	Description
157.40-156.49	0.0 - 0.91	Clay (cover material)
156.49-131.79	0.91-25.61	Refuse
131.79-131.33	25.61-26.07	Silt (ML), tan
131.33-128.38	26.07-29.02	Silt (ML), red
128.38-124.78	29.02-32.62	Silty sand (SM), brown
124.78	32.62	Schist

* MSL = mean sea level

Water table elevation above MSL = 127.01 m

TABLE C-2. LOG OF BORING 2 AT SITE C

Elevation above MSL (m)	Depth (m)	Description
145.85-144.63	0.0 - 1.22	Clay (cover material)
144.63-139.75	1.22- 6.10	Refuse
139.75-137.31	6.10- 8.54	Saturated fill
137.31-128.17	8.54-17.68	Refuse very wet
128.17-126.64	17.68-19.21	Silty sand (SM)
126.64-123.26	19.21-22.59	Sandy silt (ML)

Water table elevation above MSL = 127.26 m

TABLE C-3. LOG OF BORING 3 AT SITE C

Elevation above MSL (m)	Depth (m)	Description
145.58-145.28	0.0 - 0.30	Cover material
145.28-125.61	0.30-19.97	Refuse
125.61-124.70	19.97-20.88	Clayey sandy silt (ML), light green
124.70-123.32	20.88-22.26	Sandy silt (ML), brown with gravel
123.32-122.72	22.26-22.86	Sandy silt (ML), brown

Water table elevation above MSL = 123.02 m

TABLE C-4. LOG OF BORING 4 AT SITE C

Elevation above MSL (m)	Depth (m)	Description
136.43-135.39	0.0 - 1.04	Backfill
135.39-130.33	1.04- 6.10	Clayey sandy silt (ML), brown
130.33-125.36	6.10-11.07	Sandy silt (ML), brown
125.36-124.91	11.07-11.52	Highly weathered schist

Water table elevation above MSL = 125.40 m

TABLE C-5. LOG OF BORING 5 AT SITE C

Elevation above MSL (m)	Depth (m)	Description
131.61-131.00	0.0 -0.61	Backfill
131.00-130.09	0.61-1.52	Silty clay (CL), dark gray
130.09-127.95	1.52-3.66	Silty clay (CL), tan
127.95-127.04	3.66-4.57	Sandy silt (ML), red, tan
127.04-126.31	4.57-5.30	Sandy silt (ML), red and tan, wet

Water table elevation above MSL = 127.04 m

TABLE C-6. LOG OF BORING 6 AT SITE C

Elevation above MSL (m)	Depth (m)	Description
133.81-132.90	0.0 -0.91	Silty clay (CL), brown
132.90-130.76	0.91-3.05	Clayey sandy silt (ML), tan
130.76-126.71	3.05-7.01	Sandy silt (ML), brown

Water table elevation above MSL = 6.77 m

TABLE C-7. LOG OF BORING 7 AT SITE C

Elevation above MSL (m)	Depth (m)	Description
125.27-122.83	0.0 -2.44	Sandy silt (ML), reddish brown
122.83-121.92	2.44-3.35	Sandy silt (ML) brown, damp
121.92-121.64	3.35-3.63	Silty sand (SM) fine, green

Water table elevation above MSL = 121.71 m

TABLE C-8. LOG OF BORING 8 AT SITE C

Elevation above MSL (m)	Depth (m)	Description
132.38-131.47	0.0 -0.91	Clayey silt (ML), tan with gravel
131.47-130.25	0.91-2.13	Clayey silt (ML), brown
130.25-129.18	2.13-3.20	Sandy silt (ML), brown

Water table elevation above MSL = 130.55 m

TABLE C-9. LOG OF BORING 9 AT SITE C

Elevation above MSL (m)	Depth (m)	Description
145.55-142.70	0.0 - 3.35	Sandy silt (ML), reddish brown
142.70-133.90	3.35-11.65	Sandy silt (ML), brown
133.90-131.53	11.65-14.02	Silty sand (SM), brown

Water table elevation above MSL = 131.95 m

TABLE C-10. LIST OF SAMPLES EXAMINED FROM SITE C

Boring	Elevation of top of hole (m)	Elevation of water table (m)	Total depth (m)	Thickness of cover (m)	Thickness of refuse (m)	Elevation MW/soil interface (m)	Sampled depth interval(m)		Elevation of sampled intervals(m)		Type of sample	Sample number
							From	To	From	To		
1	157.41	127.01	32.62	0.91	24.70	131.80	25.91	26.36	131.50	131.05	physical	1P1
									131.41		chemical	1C1
									130.48		chemical	1C2
							28.96	29.40	128.45	128.01	physical	1P2
									128.34		chemical	1C3
2	145.85	127.26	22.59	1.22	16.46	128.17	18.29	18.96	127.56	126.89	physical	2P1
							18.39		127.46		chemical	2C1
							19.30		126.55		chemical	2C2
							21.44		124.41		chemical	2C3
							22.26	22.59	123.59	122.92	physical	2P2
3	145.58	123.02	22.36	0.30	19.66	125.62	19.97	20.46	125.61	125.12	physical	3P1
							20.08		125.50		chemical	3C1
							21.01		124.57		chemical	3C2
							22.28		123.20		chemical	3C3
							22.47	22.92	123.11	122.66	physical	3P2
4	136.46	125.40	11.52	NA	NA	NA	1.70	2.03	134.76	134.43	physical	4P1
							8.49	8.76	127.97	127.70	physical	4P2
							11.72		124.74		chemical	4C1
5	131.62	127.04	5.18	NA	NA	NA	4.7		126.92		chemical	5C1
6	133.81	127.04	7.01	NA	NA	NA	0.91	1.46	132.90	132.35	physical	6P1
							1.35		132.46		chemical	6C1
							2.27		131.54		chemical	6C2
							4.40		129.41		chemical	6C3

(continued)

TABLE C-10. (continued)

Boring	Elevation of top of hole (m)	Elevation of water table (m)	Total depth (m)	Thickness of cover (m)	Thickness of refuse (m)	Elevation MW/soil interface (m)	Sampled depth interval (m) From	Sampled depth interval (m) To	Elevation of sampled intervals (m) From	Elevation of sampled intervals (m) To	Type of sample	Sample number
							4.57	5.11	129.24	128.70	physical	6P2
							5.93		127.88		chemical	6C4
							7.75		126.06		chemical	6C5
7	125.27	121.71	4.12	NA	NA	NA	0.91	1.58	124.36	123.69	physical	7P1
							3.47		121.80		chemical	7C1
8	132.38	130.50	3.20	NA	NA	NA	2.24		130.14		chemical	8C1
9	145.55	132.0	14.02	NA	NA	NA	2.08		143.47		chemical	9C1
							2.98		142.57		chemical	9C2
							5.11		140.44		chemical	9C3
							7.32	7.88	138.23	137.67	physical	9P1
							9.38		136.17		chemical	9C4
							13.64		131.91		chemical	9C5

NA = not applicable

Note: All elevations are given with reference to mean sea level.